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Comparisons of Air Stripper Simulations and Field Performance Data

PEI Associates, Inc., Cincinnati, OH

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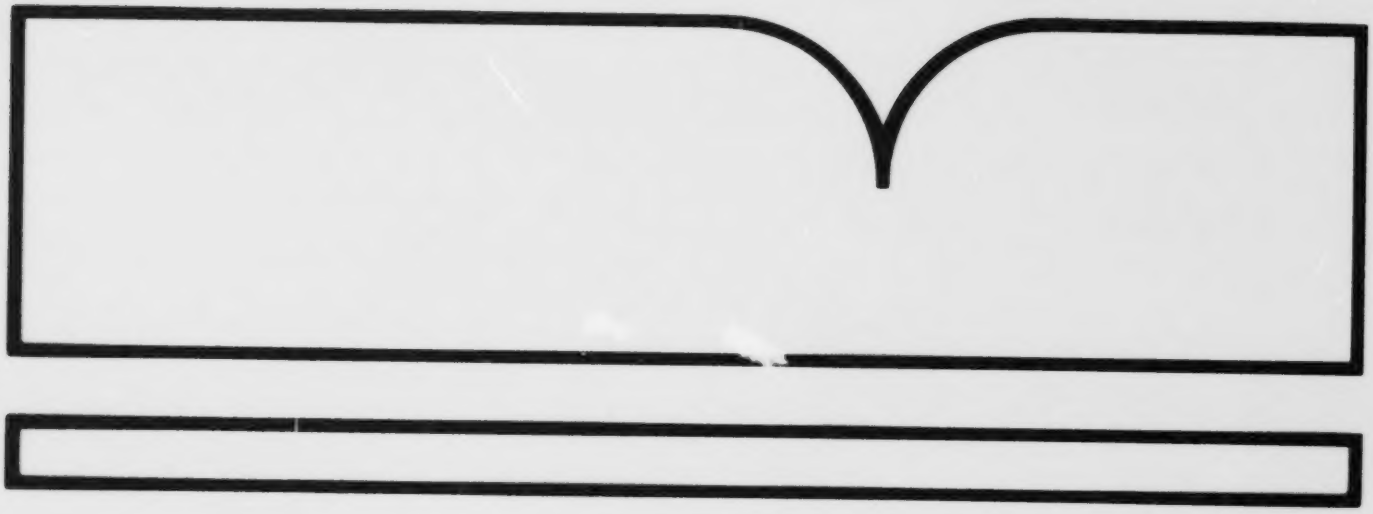

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One of the more common problems noted at Superfund sites is the contamination of ground water by volatile organic compounds (VOCs). One remedial alternative that is used to reduce or remove the VOC contamination from water is air stripping in a tower that uses either packing media or trays. The ability to strip a compound from the water depends on several factors, including the air/water ratio, the packing or tray type, and the Henry's Law value for the compounds of interest. The objective is to remove the VOCs from the water. When being considered for remediation purposes, the air stripper design should be evaluated for removal efficiency and cost of operation. One approach to this evaluation is a computerized simulation of key design parameters. Although numerous program approaches are available, a computerized process simulator (known as ASPEN) was used in this project to simulate the stripping process and to evaluate the capital and annual costs of stripper operations. The purpose of this project was to collect available design and operating data on operating air strippers and to input the design and operating parameters into the ASPEN simulator through a user interface program. The results from the ASPEN simulator were compared to the operating data gathered for the sites to determine the relative accuracy of the ASPEN model results when compared with the actual performance data.

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COMPARISONS OF AIR STRIPPER SIMULATIONS AND FIELD PERFORMANCE DATA

by

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SECTION 1

INTRODUCTION

1.1 AIR STRIPPING PRINCIPLES

One of the more common problems noted at Superfund sites is the contamination of ground water by volatile organic compounds (VOCs). In some cases, the contamination has been discovered because the VOCs have contaminated an aquifer used as a drinking water supply for a community. In other cases, the contamination is found in and near dumped or spilled materials that threaten to contaminate available water resources. One remedial alternative that is used to reduce or remove the VOC contamination from water is air stripping in a tower that uses either packing media or trays.

Air stripping generally involves the countercurrent contact between air and contaminated water by use of a packing material or trays to provide a large surface area for the transfer of VOCs from the water to the air (Figure 1). The ability to strip a compound from the water depends on several factors, including the air/water ratio, the packing or tray type, and the Henry's Law value for the compounds of interest. The objective is to remove the VOCs from the water.

When being considered for remediation purposes, the air stripper design should be evaluated for removal efficiency and cost of operation. A design evaluation may examine variations in water flow, chemical composition, contamination levels, and different stripper design considerations (air/water ratios, packing types, packing height, etc.). One approach to this evaluation is a computerized simulation of key design parameters. Although numerous program approaches are available, a computerized process simulator (known as ASPEN) was used in this project to simulate the stripping process and to evaluate the capital and annual costs of stripper operations.

The purpose of this project was to collect available design and operating data on operating air strippers and to input the design and operating parameters into the ASPEN simulator through a user interface

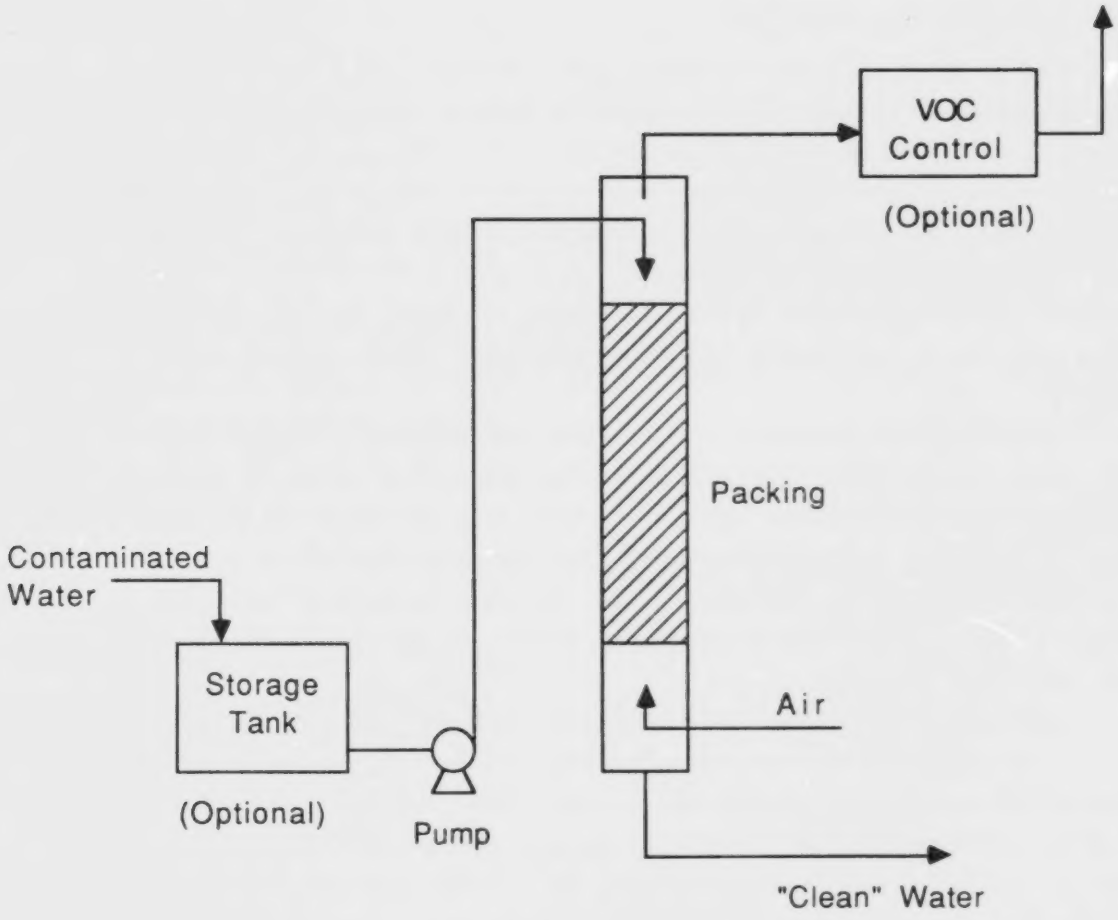

Figure 1. Diagram of the air-stripping process.

program. The results from the ASPEN simulator were compared to the operating data gathered for the sites to determine the relative accuracy of the ASPEN model results when compared with the actual performance data. A wide range of design air/water ratios, pollutant concentrations, and pollutant types were sought for comparison of actual performance versus ASPEN predictions. A total of seven sites were used for comparison purposes.

1.2 BASIC ELEMENTS OF ASPEN SOFTWARE

The ASPEN process simulation software (the acronym ASPEN represents Advanced System for Process ENgineering) is designed to aid in the evaluation of process unit operations, energy and material balances, and sizing and cost of major pieces of process equipment. One of the advantages of the ASPEN simulation software is that a complicated process can be defined by simplified modules constructed in a flowsheet style. In addition, physical and thermodynamic properties of chemicals can be accessed by built-in libraries and routines. This minimizes the need to obtain physical and thermodynamic properties for specific compounds. Using these features, an ASPEN-based model of an air stripper has been developed that includes unit operations for the control of air emissions by vapor-phase carbon adsorption or catalytic oxidation. The ASPEN air stripper module uses the Onda-correlation method to estimate mass transfer coefficients for liquid and gas phases in the calculation of stripping efficiency.

Although the programming concept of ASPEN is relatively simple, the actual programming and data input in dimensional units compatible with the ASPEN language are somewhat complicated. The development of the air stripper module eliminates the need to program in ASPEN, but data input is still required. To this end, a user-friendly-data input program was developed to generate the data input file needed to run the ASPEN air stripper module. This user interface software allows the generation of the data input file while the ASPEN air stripper module programming remains transparent to the user, and no knowledge of the ASPEN programming language or file structure is required.

1.3 USER INTERFACE SOFTWARE

The Research Triangle Institute (RTI) programmed and compiled the user interface software in an executable file in the BASIC programming language. The interface software allows a user to choose between evaluating an existing air stripper design or "creating" an air stripper design to achieve a desired removal efficiency for specified VOCs. The ASPEN simulation can evaluate performance for simultaneous removal of up to 20 VOCs from a library of approximately 400 chemicals. Default values are provided throughout the interface software, and key chemical parameters are automatically accessed by the choice of VOCs. For the seven sites used for the ASPEN comparison the model was run in "rating" mode to evaluate existing stripper designs.

The air stripper model is supplied with options for air emission controls. The user can select from the following options: 1) no control, 2) vapor-phase carbon adsorption, and 3) catalytic oxidation. He/she can also select for inclusion in system evaluation a liquid-phase carbon adsorption module for final "polishing" of the water exiting the air stripper.

1.4 INPUT/OUTPUT FORMAT

Because of its complexity and hardware requirements, the ASPEN simulation software is maintained on a VAX mainframe computer and cannot be run on a personal computer. The user interface software is designed to operate on PC's to generate the ASPEN input file required for proper execution of the program.

The ASPEN output format that is incorporated into the ASPEN simulation software provides results in a form that most people do not find very useful. Therefore, a customized output report format had to be provided that presents results in a format that the user finds both useful and readable. The output report consists of three main sections: background information on ASPEN, a summary of input data, and a performance and economic analysis. These sections provide the basis for a short engineering-style summary report of an air stripper design. The ASPEN simulation for the selected sites uses this format for the output report.

1.5 COMPARISON OF ASPEN SIMULATIONS

The project included a comparison of ASPEN simulations with the performance reported for operating air strippers with regard to the accuracy of performance and cost predictions. The operating data for seven air stripper systems representing a variety of designs and chemical species to be stripped from ground water were selected to achieve this goal. It was also deemed desirable to evaluate the operation and costs of emission controls. Of course such an evaluation was subject to data availability and quality. The results of these comparisons are discussed in the following sections.

SECTION 2

SITE SELECTION CRITERIA

The sites selected for evaluation and comparison with ASPEN simulation results had to meet several criteria. The seven sites selected for evaluation are all included on the National Priorities List (NPL) as Superfund sites. The U.S. Environmental Protection Agency (EPA) Regional Offices, State programs, and the potential sites themselves were contacted concerning the availability of data. Two reports were also used as a starting point for identifying existing air stripper systems.[2,3] Several of the sites identified in these reports as having air emission controls are not yet operational, or no data were available. Two important criteria for the ASPEN simulations were data availability and data quality. The other selection criteria will be discussed in the following subsections.

2.1 POLLUTANT TYPE

Available information on Superfund site contamination indicates that trichloroethylene is one of the most commonly identified contaminants at Superfund sites. The chemical characteristics of trichloroethylene, most notably its Henry's Law constant, make it a relatively easy compound to strip out of water. A diversity in pollutants to be stripped from ground water (representing a wide range of Henry's Law constants) was sought to evaluate the ability of the ASPEN simulation and chemical library to make accurate predictions of removal efficiencies for the various compounds. Trichloroethylene was found at six of the seven sites. Other compounds frequently identified included tetrachloroethylene (perchloroethylene), 1,1,1-trichloroethane, chloroform, dichloromethane (methylene chloride), 1,1-dichloroethylene, 1,2-dichloroethylene (cis- and trans- forms), and vinyl chloride. Table 1 presents a complete listing of the 25 compounds found at the seven selected sites. The Henry's Law constants for these compounds range from 10^{-2} to 10^{-6} atm-m^3/mole, which represents the least difficult and

TABLE 1. POLLUTANTS IDENTIFIED AT THE SELECTED SIMULATION SITES

Compound	Number of sites	Chemical abstract service (CAS) number
Acetone	1	67-64-1
Acrylonitrile	1	107-13-1
Benzene	1	1076-43-3
Carbon tetrachloride	1	56-23-5
Chloroform	3	865-49-6
1,2-Dichlorobenzene	1	95-50-1
1,1-Dichloroethane	2	75-34-3
1,2-Dichloroethane	2	107-06-2
1,1-Dichloroethylene	2	75-35-4
1,2-Dichloroethylene	3	
cis		156-59-2
trans		156-60-5
Hexachloro-1,3-butadiene	1	87-68-3
Hexachloroethane	1	67-72-1
Isobutanol	1	78-83-1
Dichloromethane	4	75-09-2
Methyl-tert-butyl ether	1	1634-04-4
Nitrobenzene	1	98-95-3
Isopropyl alcohol	1	67-63-0
1,1,2,2-Tetrachloroethane	1	79-34-5
Tetrachloroethylene	4	127-18-4
Toluene	2	108-88-3
1,1,1-Trichloroethane	4	71-55-6
1,1,2-Trichloroethane	1	79-00-5
Trichloroethylene	6	79-01-6
Vinyl chloride	3	75-01-4
Surrogates		
Ethyl-propyl ether		628-32-0

the most difficult to strip compounds, respectively. Most of the sites include several compounds, and their complexity ranges from removal of a single compound to as many as 19 compounds. Thus, the seven sites not only provide the compound most commonly found in contaminated ground water, but also provide an extensive range of contaminants for evaluation.

2.2 POLLUTANT CONCENTRATION

Contaminant levels ranging from a few parts per billion (ppb) by weight to the 100,000 ppb range were desired. At the seven sites, the average total VOC concentration levels typically ranged from 10 to 350 ppb. In nearly all cases, the actual contamination levels were below the initial design concentrations based on monitoring well data. In several cases, the actual long-term influent level was 10 to 100 times less than the design concentration. When pumping and treatment began, the concentration declined from the initial values found in monitoring wells to a substantially lower value. It is hypothesized that the sampling and monitoring wells were established under "static" conditions, and the dynamic action of pumping water established a new equilibrium.

The decrease in VOC concentrations under these circumstances result in an overdesign of the air stripper to achieve the target effluent levels. The range of pollutant concentrations at the various sites, however, allows for the evaluation of several different removal efficiencies. Many of the sites with the more common VOCs are treating water to attain levels of less than 5 ppb of specific compounds. Table 2 shows the range of influent concentrations for the most common compounds.

TABLE 2. RANGE OF CONCENTRATIONS OF THE MOST COMMONLY IDENTIFIED COMPOUNDS

Compound	Range, ppb
Chloroform	1.3 - 781
1,2-Dichloroethylene	12.5 - 100
Methylene chloride	31.4 - 8170
Tetrachloroethylene	5 - 378
1,1,1-Trichloroethane	8.2 - 1440
TCE	1.4 - 8220

2.3 WATER VOLUME TREATED

The typical air stripper treats less than 500 gal/min. The water volume treated by the seven selected sites ranges from 100 to 3500 gal/min. These air strippers represent a wide range of designs. In all but one case, the air stripper design involved a single stripping column. In the case of the air stripper treating 3500 gal/min, five parallel stripper columns are used to treat the ground water to limit the height and diameter of the column required.

2.4 AIR/WATER RATIO

Besides the physical characteristics (Henry's Law, temperature) and desired removal efficiency, the air/water ratio is an essential design parameter in the sizing and performance of an air stripper. The sites selected represent a wide range of design air/water ratios, from a low of 20 to a high of 310 (volume basis). In general, lower values result in taller columns, depending on the compounds involved. Lower air/water ratios can also result in lower gas volumes to be treated by additional gas emission control systems and higher VOC concentrations in the uncontrolled gas stream. In general, lower air/water ratios reduce VOC control costs and result in more effective operation of VOC controls. Actual designs typically represent a compromise between compounds to be treated, the variability in the influent concentrations, and total gas volume to be handled. Most new designs use air/water ratios of 125 or less.

An additional factor encountered during the data acquisition was the use of high-temperature air strippers (HTAS). Two of the systems use HTAS to improve removal efficiency of hard-to-strip compounds [e.g., alcohols, acetone, methyl ethyl ketone (MEK)] without excessively increasing the air/water ratio. The operation at elevated temperature (greater than 140°F) modifies the Henry's Law constants for these compounds. High-temperature strippers increase the energy costs for preheating the water.

2.5 CONTROL EQUIPMENT

The two control equipment options for the ASPEN air stripper simulation modules made it desirable to obtain data for comparable systems from actual operating strippers. The air stripper report produced by Radian indicated the existence of such air strippers, most of which operate without VOC controls.[1] Four of the 12 sites used an incineration technique that was not compatible with the ASPEN module (direct incineration) for VOC controls. The remaining sites were either not operating or no data were available for use in this study. Table 3 includes all sites currently operating with VOC controls. Three of the sites shown in this table are included in the comparison study. Several Superfund sites also propose controls for future air stripping operations.

Three of the seven sites selected for the ASPEN performance comparison used some kind of VOC control. The Verona Well Field Site uses vapor-phase carbon adsorption. The carbon, however, is not regenerated on site; it is changed every 6 to 12 months, as necessary. The Western Processing Site also uses vapor-phase carbon adsorption to control VOC emissions. This system differs in that it is regenerated by gases from a direct-fired incinerator (CADRE), which, in turn, destroys the VOCs released from the carbon beds during regeneration. The Gilson Road Site uses the boiler that preheats the stripper water to its operating temperature as an incinerator to destroy VOCs liberated by the air stripper.

In the future, many more air strippers will probably include VOC controls. For this project, however, only a limited number of sites could provide useful data. No data were available from sites using catalytic oxidation; however, this is still considered a possible control technology for air strippers. Catalytic oxidation systems are also being considered and proposed for in situ soil vapor extraction, which has similar gas-stream characteristics. Direct incineration or hybrid systems such as CADRE are not currently included as ASPEN options.

TABLE 3. CURRENTLY OPERATING FACILITIES USING AIR EMISSION CONTROLS ON AIR STRIPPERS

Facility name	City	State	Type[a]	Major contaminants[b]	Type[c]	Control required, Y/N
BKK Landfill	West Covina	CA	LF	Landfill leachate	Flare	
City of Plainfield	Plainfield	NJ	DW	PCE, TCE	GAC	
Hughes Aircraft	Tuscon	AZ	GW	TCE, DCA, TCA	GAC	Y
Lowry Landfill I	Denver	CO	LF	1,1-DCA, 1,2-DCA	GAC	Y
Verona Well Field	Battle Creek	MI	GW	1,1,1-TCA, 1,1-DCA, PCE, TCE	GAC	Y
McClellan AFB	Sacramento	CA	GW	MEK, acetone, various VOC	INCIN	Y
Gilson Road	Nashua	NH	GW	MeOH, EtOH, acetone MEK, Tol, others	INCIN	Y
Chem Central	Grand Rapids	MI	GW		GAC	
Western Processing	Kent	WA	GW	1,2 DCA, Tol, PCE, TCE, TCA, chloroform, methylene chloride, others	GAC	Y
Unifirst	Williamstown	VT	GW	PCE	GAC	Y
Chem-Dyne	Hamilton	OH	GW		GAC	
Palos Verdes Landfill	Palos Verdes	CA	LF	Landfill leachate	Flare	

[a]LF = landfill, DW = drinking water, and GW = ground water.

[b]PCE = Tetrachloroethylene; TCE = trichloroethylene; TCA = 1,1,1-trichloroethane; 1,1-DCA = 1,1-dichloroethane; 1,2-DCA = 1,2-dichloroethane; MEK = methyl ethyl ketone; MeOH = methanol; EtOH = ethanol; Tol = toluene.

[c]INCIN = incineration; GAC = granulated activated carbon.

2.6 DATA AVAILABILITY AND QUALITY

A major limitation in obtaining data was the assurance that available data were of good quality. Some sites were eliminated because the number of contaminants were limited to one or two components already well represented (e.g., trichloroethylene). In most cases, however, complete or nearly complete design or operating data were not readily available from the sites. For example, in some cases, initial contacts with Agency or site personnel indicated that complete design information was not available or that operating data were limited. The lack of performance data for VOC control systems was particularly a problem at sites that use emission controls. In other cases, there was a reluctance to provide information, either because of legal or political situations or because of the effort required to provide the information. Where data were not forthcoming, the sites were dropped from further consideration in this project.

For the seven sites selected, the design and performance data are relatively complete and are of sufficient quality to provide reasonable accuracy. One area in which data completeness was a problem involved costs. In general, the basis of the cost values provided was difficult to ascertain. The costs for the Brewster Well Field Site and the Hicksville MEK Site were the exception. The allocation of costs was well defined for these sites. For the remaining sites, only general costs were provided, and documentation of what was included in the direct and indirect costs was limited.

SECTION 3

SITE BACKGROUND SUMMARIES

As discussed in Section 2, the seven sites selected represent a substantial diversity in design, contaminants, concentrations, and VOC controls. Although none of the sites is entirely representative of the majority of operating air strippers, together they provide a wide range of parameters for the ASPEN simulation process to use for comparison of actual and simulation values. The air stripper designs at these sites also should be within the range of designs and concentrations expected in future site remediations. This section presents background information on each of the selected sites. Table 4 summarizes pertinent information, and Appendix A provides detailed design and operating information.

3.1 TACOMA WELL 12A

The Tacoma Well 12A Site is located in the southern part of Tacoma, Pierce County, Washington. During the summer months, Well 12A supplies the water-processing plant with the higher daily average and peak flows associated with summer water usage. Contamination of the well was first discovered in 1981, at which time the well was shut down. No alternative supply of water could be developed to replace the lost production of this well (3500 gal/min). In the meantime, the site was placed on the NPL and became eligible for Superfund monies.

During the time the source and extent of aquifer contamination were being determined, an interim remedial action was planned to return the well to service while the VOCs were being removed from the well water. The plan called for the use of a pilot-scale stripper to document the feasibility of air stripping as a remedial alternative and the subsequent scale-up of the stripper if the pilot-scale treatment proved successful. The air stripper would then be installed and operated to remove VOCs from the water. A short time frame of 11 months was planned for implementation of this plan.

TABLE 4. SUMMARY OF SELECTED SITES

Site number	Site name	Location	Primary contaminants	VOC controls	Comments
1	Tacoma Well 12A	Tacoma, WA	Tetrachloroethane Trichloroethylene Dichloroethylene	No	5 towers to handle 3500 gal/min
2	Rockaway Township	Rockaway Township, NJ	Trichloroethene Methyl-tert-butyl ether Diisopropyl ether	No	Other compounds identified
3	Brewster Well Field	Brewster, NY	Tetrachloroethylene Trichloroethylene Dichloroethylene	No	
4	Verona Well Field	Battle Creek, MI	1,1,1-Trichloroethane Trichloroethylene Tetrachloroethylene Dichloroethylene Other VOCs	Yes	Nonregenerable vapor-phase GAC
5	Western Processing	Kent, WA	Dichloromethane Trichloroethylene 1,1,1-Trichloroethane Methyl ethyl ketone Other VOCs	Yes	Vapor-phase GAC with incinerator used during regeneration
6	Hicksville MEK Spill	Hicksville, NY	Methyl ethyl ketone	No	HTAS
7	Gilson Road (Sylvester's) Site	Nashua, NH	Isopropanol Acetone Toluene Dichloromethane	Yes	HTAS boiler used for incineration

The remedial investigation determined potential areas and sources of aquifer contamination. The VOC concentration in the water varied because seasonal startup of the well drew in essentially uncontaminated or only slightly contaminated water before drawing in the contaminated plume resulting from the reversal of the normal aquifer flow.

Four chlorinated organic solvents were identified in the well water. These were 1,1,2,2-tetrachloroethane, trans-1,2-dichloroethylene, trichloroethylene, and tetrachloroethylene. The pilot-scale testing included various air/water ratios and column packings at VOC concentrations at or near the maximum levels encountered during normal seasonal operations. Successful operation of the pilot-scale unit indicated that air stripping could be used to remove VOCs from the water. Of the four compounds, 1,1,2,2-tetrachloroethane was the most difficult to remove and had the highest design concentration (300 ppb).

The scale-up of the air stripper design called for five parallel towers packed with 1-inch saddles. The use of five towers allowed for shutdown of one tower for maintenance while maintaining the overall removal efficiency. Each tower handles 700 gal/min. The design air/water ratio is 310 ft^3 air/ft^3 water, which represents the highest value of air/water ratio in the seven selected sites. The Tacoma Well 12A Site also represents the largest water treatment volume of the seven sites. As is typical with many sites, actual operation usually results in influent levels substantially lower than the initial design value. The air stripper, however, must be designed to provide a given effluent level for the highest concentrations of the various contaminants. The compound that is most difficult to strip may also be a controlling factor. In this case, the 1,1,2,2-tetrachloroethane fit both criteria--the highest influent concentration and the most difficult to strip. In actual operation, the other compounds are undetectable in the effluent.

The high air/water ratio results in lower packing heights and reasonably sized multiple stripping towers; however, substantial energy is required to move 29,000 ft^3/min through each tower. These high gas volumes and the extremely dilute VOC concentration in the gas stream make selection of any VOC option difficult. The system, however, has worked well. Table 5 summarizes the key parameters, and Figure 2 is a process flow diagram. Given these tradeoffs, the design selected today might differ from that selected in 1982.

TABLE 5. SUMMARY OF SELECTED DESIGN DATA FOR TACOMA WELL 12A

Number of stripper columns: 5
Water volume treated: 3500 gal/min (700 gal/min per column)
Air volume: 145,000 cfm (29,500 cfm per column)

Tower height - 32 ft
Tower diameter - 12 ft
Packing height - 23 ft
Packing type - 1 in. plastic saddles

Air/water ratio - 310 (volume basis)
Air mass velocity - 1.56 kg/m^2-s
Water mass velocity - 4.16 kg/m^2-s

CONTAMINANT LEVELS

Chemical	Design, ppb	Actual, ppb
1,1,2,2-Tetrachloroethane	300	40.9
trans-1,2-Dichloroethylene	100	14.3
Trichloroethylene	130	44.6
Tetrachloroethylene	5	0.9

Designed for 89 percent removal of 1,1,2,2-Tetrachloroethane

No emission controls

Date of initial operation: July 1983

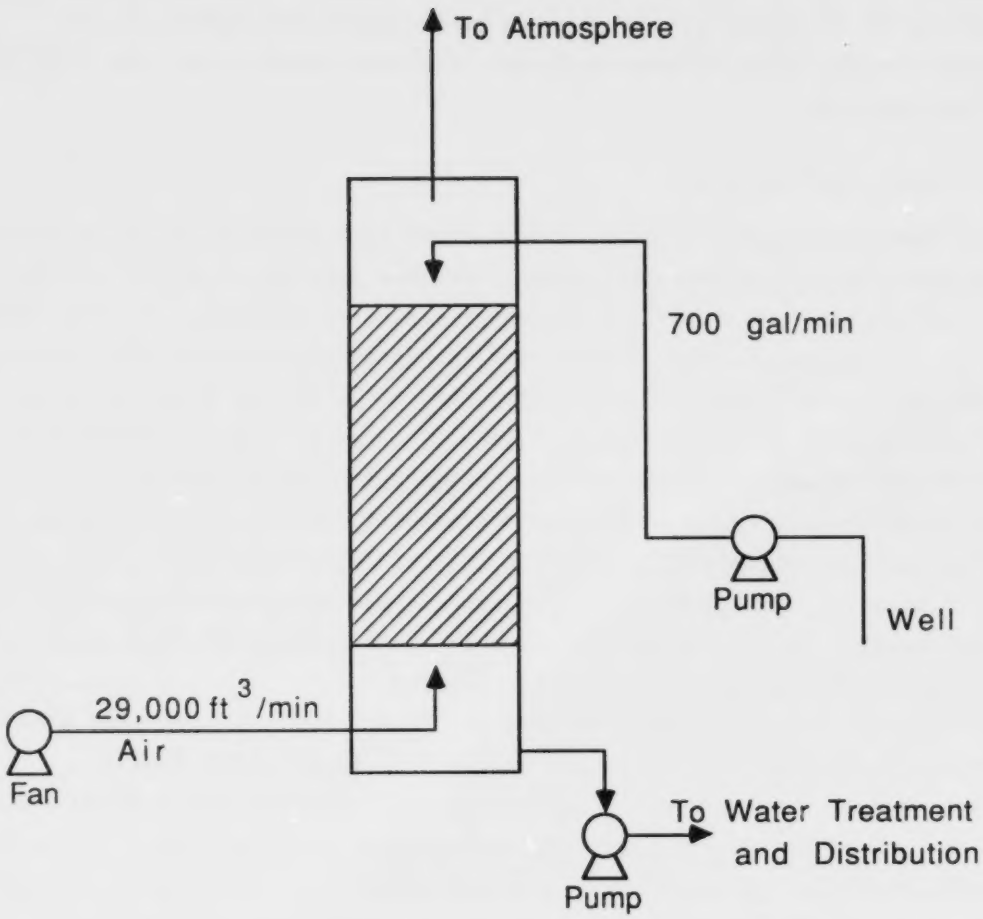

Figure 2. Process flow diagram for Tacoma Well 12A.

Further remedial actions involving the suspected source of contamination are being planned for this site. These include in situ vapor extraction of the contaminated soil and the pumping and liquid-phase carbon adsorption treatment of the highly contaminated aquifer layer directly under and surrounding the source of contamination. These actions should reduce the availability of contaminants and substantially reduce the extent of the contaminant plume, which would reduce the long-term remediation time required to achieve cleanup.

3.2 ROCKAWAY TOWNSHIP SITE

The Rockaway Township Site is a well field that supplies drinking water to this township in northern New Jersey. Maximum pumping capacity is 1900 gal/min and the nominal flow from three wells is 1400 gal/min. In late 1979 [prior to the Comprehensive Environmental Response Compensation and Liability Act (CERCLA)], trichloroethylene was detected in two of the three wells at levels ranging from 50 to 220 ppb. Initially, these two wells, which were nearest to the suspected source of the contamination, were removed from potable water service. One of the two contaminated wells was operated as a "blocking" well to protect the remaining uncontaminated well, and the contaminated water was pumped directly into a small stream. Alternatives were investigated to replace or remediate the lost production from these wells while the blocking well was being operated.

In October 1980, the remaining well was found to be contaminated with two compounds: diisopropyl ether and methyl-tert-butyl ether from a different suspected source of contamination. The alternatives available to the township were to obtain water from surrounding municipalities, to develop a new well field, or to remediate the ground water. In the interim, the site was placed on the NPL pending selection and implementation of remedial alternatives.

Initially, a liquid-phase granulated activated carbon (GAC) adsorption system with an expected carbon life of 6 to 8 months before regeneration was necessary was selected to remove VOCs from the ground water. Actual operation, however, showed that the operating time before breakthrough of the two ether compounds was between 4 and 6 weeks, which presented an

unsatisfactory operating condition and cost (approximately $32,000 per carbon change-out).

Pilot-scale tests with well water were begun to investigate the feasibility and design requirements for an air stripper. The two ether compounds are more difficult to strip than trichloroethylene because their Henry's Law constants are nearly an order of magnitude lower. The two ether compounds were producing odor and taste problems in the water and were determined to have an extremely low taste threshold. It was also determined that diisopropyl ether was the major compound associated with taste and odor problems. Consequently, any design necessary to remove the ether compounds was found to remove trichloroethylene to satisfactory levels during the pilot-scale testing.

Scale-up of the pilot test air stripper resulted in the design summarized in Table 6. The design basis selected was 99.9 percent removal of diisopropyl ether, based on an influent concentration of 4000 ppb. This influent level was based on hydrogeological studies and the estimated spill quantity. The target value of 4 ppb for diisopropyl ether was considered low enough to avoid taste and odor problems. The air stripper was placed in service in February 1982. The liquid-phase GAC system has been held in reserve should maintenance be required on the stripper or should final polishing of the treated water be required.

In actual operation, the levels of diisopropyl ether and methyl-tert-butyl ether only increased to levels of 50 to 60 ppb. The trichloroethylene levels were initially in the range of 200 to 300 ppb, but they fluctuated greatly. The diisopropyl ether and methyl-tert-butyl ether levels remained relatively constant from the last half of 1981 through October 1982, at which time they gradually decreased. Diisopropyl ether has remained undetectable since February 1982, and methyl-tert-butyl ether levels have very slowly declined over the years. The concentration of trichloroethylene in the water has also decreased to relatively low levels over the years, but samples taken every 2 weeks still show substantial variation in the influent concentration. Benzene and toluene, which were detected in monitoring wells, have not yet been detected in the stripper influent. Several other compounds, however, have been discovered since the system has been in operation, including 1,1-dichloroethylene, cis-1,2-dichloroethylene, chloroform,

TABLE 6. SUMMARY OF SELECTED DESIGN DATA FOR ROCKAWAY TOWNSHIP

Number of stripper columns: 1
Water volume treated: 1400 gal/min
Air volume: 37,500 cfm

Tower height - 35 ft
Tower diameter - 9 ft
Packing height - 25 ft
Packing type - 3 in. Tellerettes

Air/water ratio - 200 (volume basis)
Air mass velocity - 3.60 kg/m^2-s
Water mass velocity - 14.91 kg/m^2-s

CONTAMINANT LEVELS

Chemical	Design, ppb	Actual, ppb
Trichloroethylene	300	28.3
Diisopropyl ether	4,000	No longer detected
Methyl-tert-butyl ether		3.2
Tetrachloroethylene	5	0.9

Contaminant levels for other compounds not specified in the design. Removal efficiency specified: 99.9 percent diisopropyl ether

No emission controls

Date of initial operation: July 1982

1,1,1-trichloroethane, and (occasionally) dichloromethane and 1,1-dichloroethane. Some doubt exists as to whether the last two compounds are actually present or are a result of laboratory problems, as they are observed intermittently and at very low concentrations. The possible source of these additional compounds had not been determined; however, the two dichloroethylene compounds could be decomposition products of the original trichloroethylene spills as the trichloroethylene slowly breaks down in the aquifer. The other compounds may indicate that some other spill has occurred recently or that contamination from a more distant source has finally traveled through the aquifer. In any case, the air stripper has sufficient design capacity to remove these other compounds.

The design liquid volume of 1400 gal/min (peak at 1900) and a nominal air/water ratio of 200:1 place this system in the upper range for both design parameters. The design concentrations were relatively high, but current operation and influent conditions place this system on the lower end of the contaminant concentration scale. This system is not equipped with any VOC controls for air emissions. Table 6 summarizes the design and operating parameters. Figure 3 is a process flow diagram.

A point of interest not modeled by ASPEN, but one that has an impact on water quality, is the effect of the air stripper operation on other water quality parameters. The influent water is slightly acidic, as it contains a small quantity of CO_2 dissolved as carbonic acid in the water. The water also contains a small quantity of dissolved iron (FeO). As the water passes through the air stripper and comes in intimate contact with air, the CO_2 is stripped from the water, which alters the pH. This also oxidizes the iron to Fe_2O_3, which is much less soluble in a neutral or alkaline condition than in an acidic environment. Whereas such a change in equilibrium has not affected operation of the air stripper, it has affected the final water quality and the potential for "scale" within the distribution system and at the point of use. The township currently plans to use a sequestering agent to combine with the iron in the water to prevent further problems with iron.

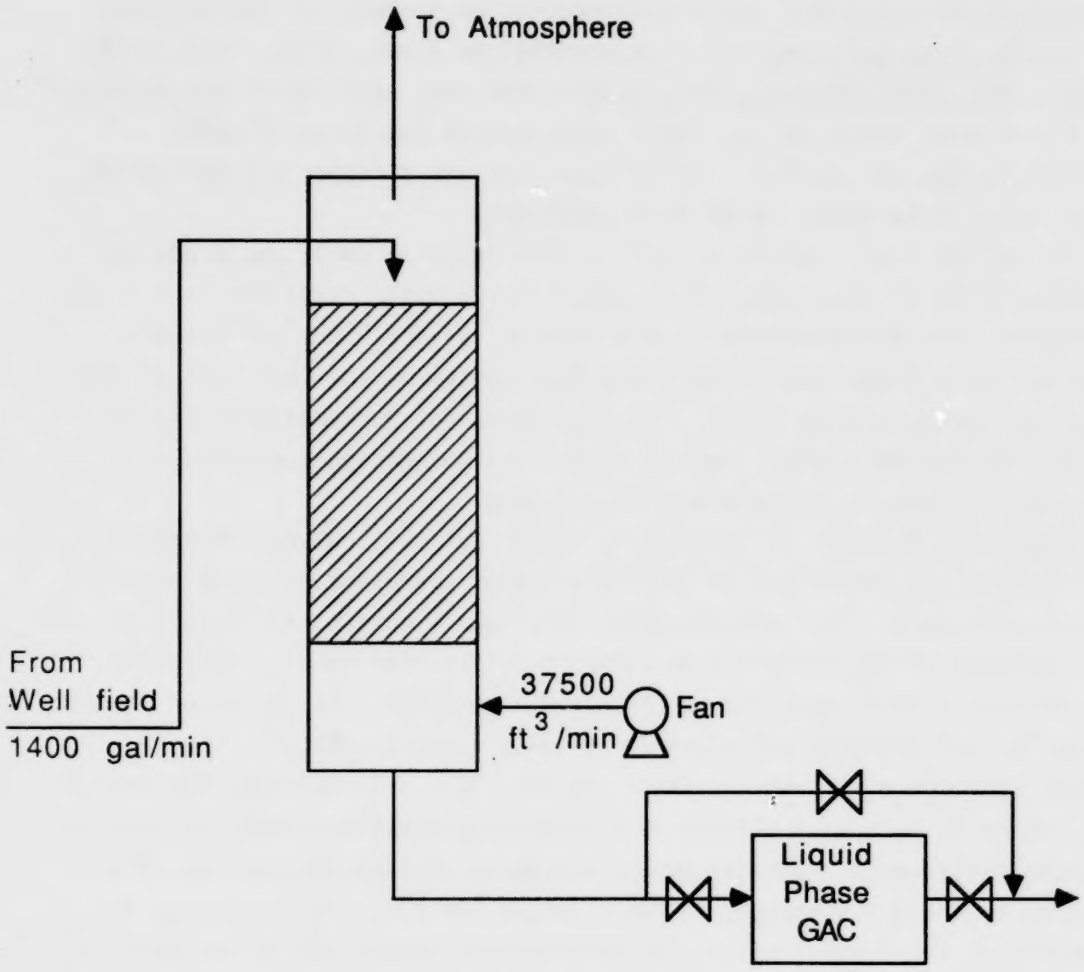

Figure 3. Process flow diagram for Rockaway Township.

3.3 BREWSTER WELL FIELD NO. 1

The Brewster Well Field Area No. 1 is composed of nine wells, and when combined with the output of Well Field Area No. 2, supplies drinking water to the Village of Brewster in Putnam County, New York. Sampling conducted in August 1978 indicated that tetrachloroethylene and trichloroethylene were detected at levels of 166 and 5 ppb, respectively, or an overall value of 171 ppb. Testing the following month showed levels at 174 ppb and 220 ppb for total VOCs, which prompted shutting down the well field. The need to resume production to maintain an adequate water supply resulted in pilot-scale testing and full-scale operation of an air stripper to treat the contaminated ground water. This air stripper was placed in operation in October 1984. Subsequently, contamination of Brewster Well Field Area No. 2 and a deep well (designated DW-2) were observed and are the subject of a recent Remedial Investigation/Feasibility Study (RI/FS) and Record of Decision (ROD) indicating another air stripper with VOC emission controls as the preferred treatment technology.

The compounds of primary interest at Brewster Well Field No. 1 were tetrachloroethylene, trichloroethylene, cis- and trans-1,2-dichloroethylene, and vinyl chloride. Occasionally a variety of trihalomethanes were found in the well water, but they were believed to be caused by chlorination of the well water and not directly related to a source of contamination. In addition to a full-scale stripper, several pilot-scale strippers were also tested for removal efficiency with various packings and air/water ratios. The test data showed that at the influent concentrations measured, a minimum air/water ratio of 20:1 (volume basis) was needed to meet Maximum Contaminant Levels (MCLs) specified by the Safe Water Drinking Act. The full-scale column typically operates at an air/water ratio of 50:1.

The water volume handled by this air stripper is 300 gal/min, which is considered to be in a range typical of most air strippers. The air/water ratio of 50:1 is also considered typical for this application, as are the concentrations of the pollutants in the water. Table 7 summarizes the stripper design parameters, and Figure 4 is a process flow diagram for Brewster Well Field.

The estimated cost of construction and the assumptions used in the development of operating and maintenance costs for this system appeared to be

TABLE 7. SUMMARY OF SELECTED DESIGN DATA FOR BREWSTER WELL FIELD

Number of stripper columns: 1
Water volume treated: 300 gal/min
Air volume: 2000 cfm

Tower height - 27 ft
Tower diameter - 4.75 ft
Packing height - 17.75 ft
Packing type - 1 in. Saddles

Air/water ratio - 50
Air mass velocity - 0.28 kg/m^2-s
Water mass velocity - 11.41 kg/m^2-s

CONTAMINANT LEVELS

Chemical	Design, ppb	Actual, ppb
Tetrachloroethylene	215	200
Trichloroethylene	77	30
1,2-Dichloroethylene	68	38
Vinyl chloride	2	ND

Designed for removal down to 5 ppb for all compounds except vinyl chloride (nondetectable levels).

Date of initial operation: October 1984

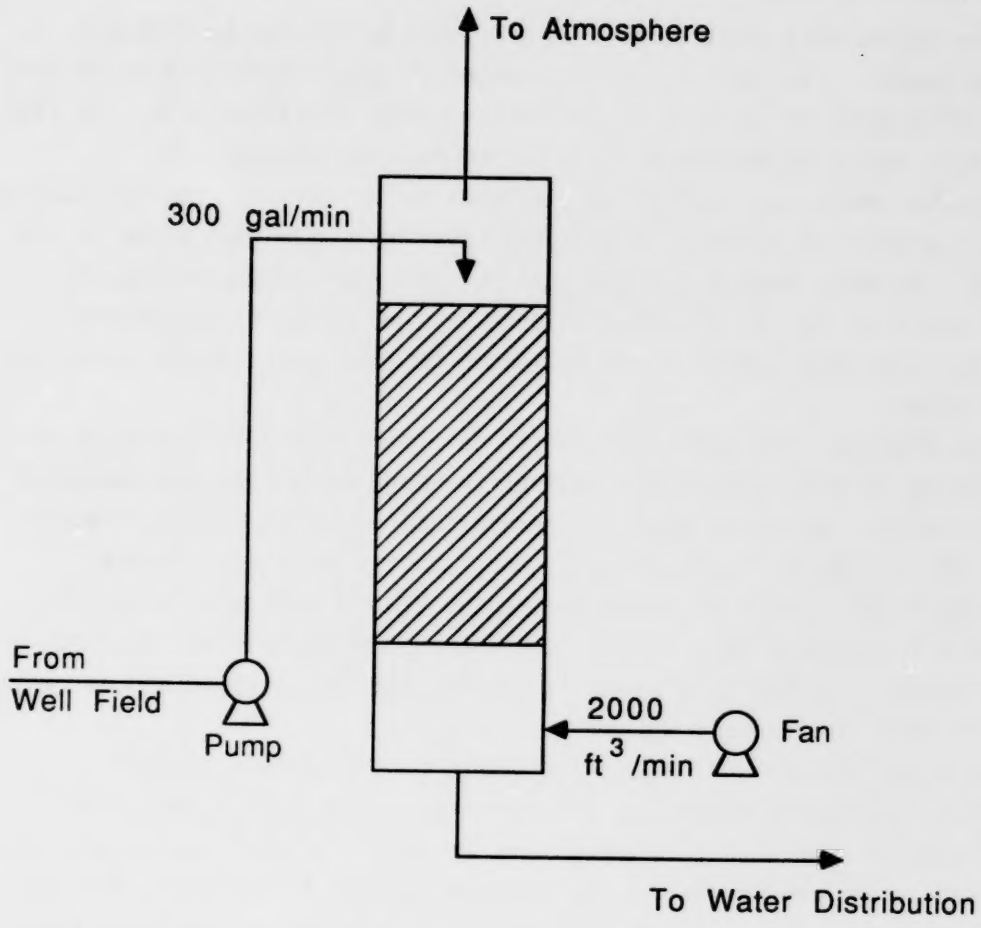

Figure 4. Process flow diagram for Brewster Well Field.

well documented. Costs of major components (stripper column, piping, instrumentation, etc.) were outlined to provide total capital costs instead of a single reported capital cost value without documentation.

3.4 VERONA WELL FIELD

The Verona Well Field Site is located near Battle Creek, Michigan, in Calhoun County. This well field is composed of approximately 30 wells that supply potable drinking water to the Battle Creek, Michigan, area. In 1981, detectable levels of VOCs were found during routine testing. The contaminated wells were identified and taken out of service, and the pumping load was shifted to other wells and away from the contaminant plume in the aquifer. By 1984, however, it was apparent that the summer maximum-day demand could not be met and other alternatives needed to be considered. These included development of new wells and the treatment of the contaminated ground water.

The five contaminated wells were to be placed back into operation to act as blocking wells to protect the rest of the well field from the spread of contamination. An air stripper was recommended as the most cost-effective method of treatment. Under interim removal action authority, however, operation of the five wells began before the air stripper was installed. Temporary treatment with a liquid-phase GAC adsorption unit was applied. This provided a unique opportunity to compare the installation and operating costs of both liquid-phase GAC and air stripping.

Michigan regulations require the use of best available control technology (BACT) for control of air emissions where any new source of carcinogens or suspected carcinogens are involved. In this case, vapor-phase activated carbon adsorption was the selected control technology. The cost of this system was included in the initial feasibility and cost-effectiveness study.

The compounds of concern found in monitoring wells were 1,1-dichloroethane, 1,2-dichloroethane, 1,1,1-trichloroethane, 1,1-dichloroethylene, cis-1,2-dichloroethylene, trichloroethylene, and tetrachloroethylene. It should be noted that concentrations from monitoring well data prior to startup were 15 times higher than those found at the

influent of the liquid-phase GAC adsorption system or the air stripper once operation began.

The air stripper was designed to handle a nominal water flow of 1950 gal/min (maximum of 2500 gal/min). This places the design capacity of the column on the high-end of stripper designs for water volume treated. This design, however, also incorporates a minimal air flow design to reduce the gas volume handled by the vapor-phase GAC. Thus, the operating air/water ratio is 20:1, the lowest within the group of the seven selected sites. This design results in a very tall stripping column with a packing height of 40 feet. Table 8 summarizes the design data. Figure 5 is a process flow diagram for the site.

The air passes through the air stripper, an induced-draft fan, and an indirect-fired natural gas heater and into two vapor-phase carbon adsorbers to adsorb VOCs from the gas stream. The natural-gas-fired heater is used to lower the relative humidity of the gas stream to less than 50 percent by providing a 30° to 35°F temperature increase to improve vapor-phase GAC performance. The vapor-phase GAC system does not have any provision for onsite regeneration. Based on the design parameters, change-out of carbon (to be regenerated offsite) was to be required approximately once a year.

The operation of the liquid-phase GAC adsorption system continued for 17 weeks. It was terminated and removed once the air stripper system became operational. The performance of the liquid-phase system indicated that liquid-phase carbon would have to be replaced at least every 6 months. When the system was shut down, it was discovered that breakthrough had occurred for the 1,2-dichloroethylene, 1,1,1-trichloroethane, and 1,1-dichloroethane.

Since its operation began in 1984, occasional tests were made of the vapor-phase GAC system, but the daily levels were not routinely monitored during the tests. Initial test results for the air stripper and vapor-phase GAC indicated high removal efficiencies of VOC from the water and air. When VOC concentrations at the outlet of the vapor-phase GAC system increased, the carbon was replaced. The concentration of VOCs in the water influent remained relatively constant. The potential source of the contamination was identified and in 1987 and early 1988, a removal action was implemented to reduce the areas of highest contamination. Part of this removal action included the use of the stripper's "extra VOC stripping capacity," which was

TABLE 8. SUMMARY OF SELECTED DESIGN DATA FOR VERONA WELL FIELD

Number of stripper columns: 1
Water volume treated: 1950 gal/min
Air volume: 5000 cfm

Tower height - 65 ft
Tower diameter - 10 ft
Packing height - 40 ft
Packing type - 3.5 in. polypropylene pall rings

Air/water ratio - 20 (volume basis)
Air mass velocity - 0.39 kg/m^2-s
Water mass velocity - 16.85 kg/m^2-s

CONTAMINANT LEVELS

Chemical	Design, ppb	Actual, ppb
1,1-Dichloroethane	34	5.7
1,2-Dichloroethylene	8	ND
1,1,1-Trichloroethane	150	12.1
cis-1,2-Dichloroethylene	229	11.1
1,1-Dichloroethylene	11	ND
Trichloroethylene	62	1.1
Tetrachloroethylene	94	9.2

Designed to remove contaminants to less than 5 ppb.

Vapor-phase GAC adsorption system for VOC emissions control
Number of beds: 2
Bed diameter: 10 ft
Bed depth: 4 ft
Carbon weight: 9,500 lb
Carbon type: Calgon BPL, 4x6 mesh
Air preheater included (indirect, natural gas-fired)
Nonregenerable system, change once/year
Removal efficiency: 90 percent

Date of initial operation: September 1984

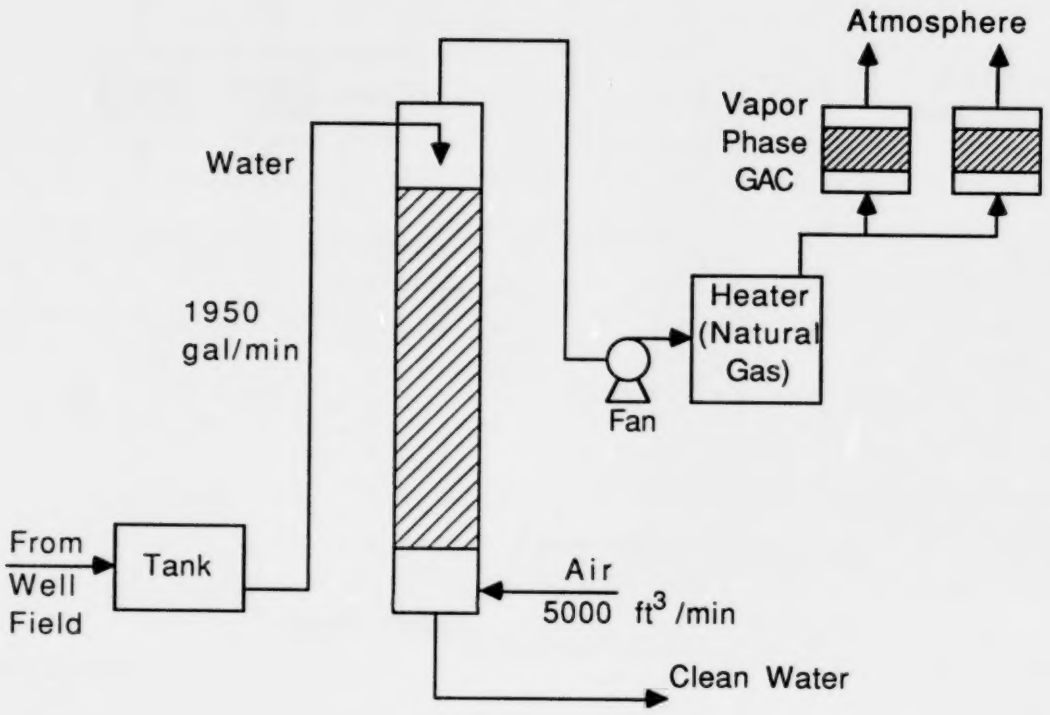

Figure 5. Process flow diagram for Verona Well Field.

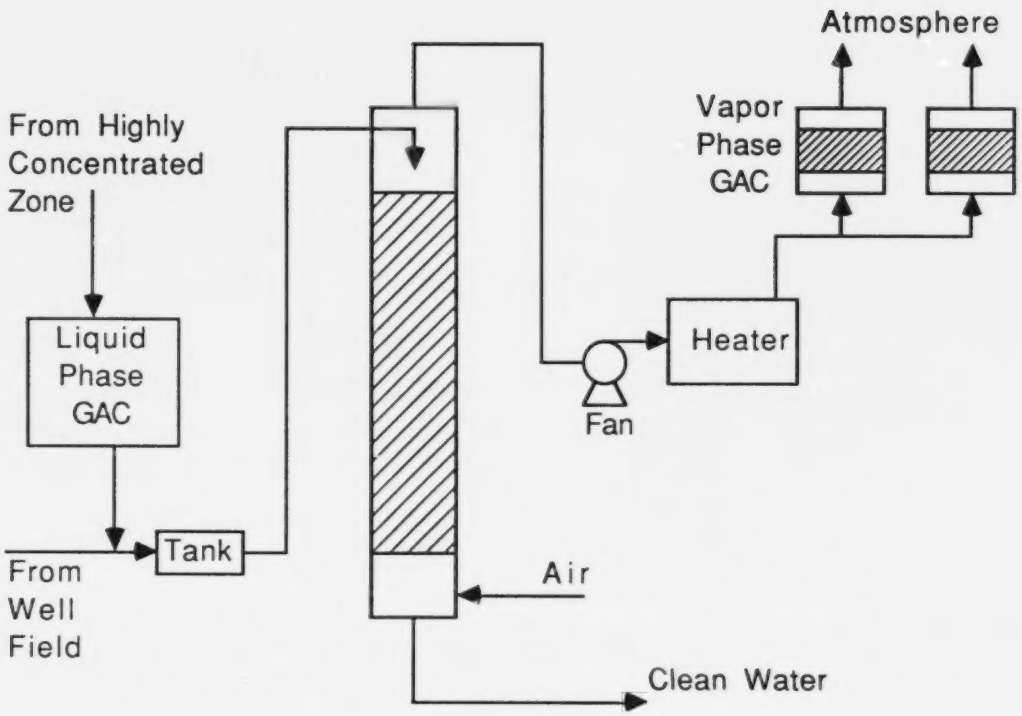

Figure 6. Process flow diagram for Verona Well Field during removal action of highly contaminated zone.

not being used because influent VOC levels were substantially below design levels. Ground water was pumped from the aquifer at and near the source of the contamination and pretreated by passing it through temporary liquid-phase GAC adsorbers to remove the bulk of VOC contaminants. This arrangement is shown in Figure 6. Additional compounds not normally found in the air stripper influent include dichloromethane and vinyl chloride. These data were included in the ASPEN comparison data set because they represented elevated levels of VOC being sent to the stripper. All other parameters (water and air flow) remained constant. The data provided also included test data from the vapor-phase GAC adsorption system. This removal action has been completed and the system has been returned to its original design. No other major problems have been noted for this system.

Site installation costs, for the air stripper system and estimated operation and maintenance costs were provided. A complete breakdown of all the capital costs was not available. Costs for operation and maintenance, however, were provided for energy and annual vapor-phase GAC replacement.

3.5 WESTERN PROCESSING SITE

The Western Processing Site is located in Kent, Washington (near Seattle) in King County. The 13-acre site was originally a hazardous waste treatment, storage, and disposal facility (TSDF) under the Resource Conservation and Recovery Act (RCRA) regulations. Contamination of surface and ground water was discovered, and a RCRA Corrective Action Order was issued for the site in 1980. The site continued to operate until it filed for bankruptcy because it was unable to comply with the corrective action order. The site was placed on the NPL in 1982.

A series of removal actions included the drums dumped, stacked, or buried at the site and the contaminated surface soils. The site is located next to a tributary of the Green River, and the water table depth ranges between 3 and 12 feet with an average depth of 6 feet to the top of the water table. This shallow aquifer extends downward some 75 feet. Extensive sampling of this aquifer revealed 87 priority pollutants and 12 other hazardous pollutants. Forty-nine of the compounds are either known or suspected carcinogens. Twenty-nine samples wewre present in concentrations above 1000 ppb.

TABLE 9. CONCENTRATION RANGE FOR SELECTED VOC CONTAMINANTS AT THE WESTERN PROCESSING SITE

Compound	Range, µg/liter
Benzene	77 to 2,200
1,2-Dichloroethane	16,000
1,1,1-Trichloroethane	100 to 340,000
1,1-Dichloroethane	320 to 33,000
Chloroform	130 to 27,000
1,1-Dichloroethylene	87[a]
trans-1,2-Dichloroethylene	390,000[a]
Ethylbenzene	32[a]
Dichloromethane	1,200 to 720,000
Fluorotrichloromethane	920[a]
Tetrachloroethylene	37 to 50
Toluene	110 to 22,000
Trichloroethylene	830 to 210,000
Vinyl chloride	360[a]

[a]Noted in only one sample.

The site is extremely heterogeneous and varies widely in both types of contaminants and their concentrations. Table 9 presents a partial listing of the range of concentrations found in seven monitoring wells. Of the 14 compounds listed in Table 9 chloroform, dichloromethane, 1,1,1-trichloroethane, and trichloroethylene appeared to be the most widely distributed. In addition to these VOCs, many semivolatile and nonvolatile organics, were found as were a number of inorganic species.

The extreme variability in the concentrations made it rather difficult to select a design that would meet Safe Water Drinking Act Maximum

Contaminant Levels (MCL) for these VOCs. The entire treatment system also needed to address inorganic materials as well as the semi- and nonvolatile organic compounds. Air stripping was the selected remedial alternative for VOCs and is the first of many steps in the water-treatment process.

Two stripper towers are used at this site. One tower, the larger of the two, is designated as the "extraction" tower. This tower treats ground water from a larger area of the site. The smaller of the two towers, designated as the "trans-tower" for removal of trans-1,2-dichloroethylene, receives its water from three contaminated wells located across the tributary from the main site. Both air strippers vent into an induced-draft fan (one for each tower), and the gases are then combined and heated to reduce relative humidity.

Emission controls were required on this system and a vapor-phase GAC adsorption system is also used. The system is a two-bed CADRE system. The CADRE system differs from a conventional steam-regenerated GAC system in that it uses an incinerator to generate heat for desorption and regeneration of the carbon beds. This same incinerator also combusts the VOCs as they are desorbed from the GAC. The principal advantage to this system is that the incinerator treats a much smaller gas volume with much higher VOC concentrations than normally exits the strippers, which lowers the energy costs. It also eliminates the handling of the liquid wastes that would be generated by conventional steam regeneration. Figure 7 is a schematic of this system.

The two air strippers are designed around "primary" and "secondary" air and water flow rate values. The primary values represent the initial lower volume operating values for the site, when the contaminant concentrations would be expected to be the highest. The secondary values represent the higher air and water flow rates that occurred when remediation was well under way and contaminant concentrations were somewhat reduced.

As mentioned earlier, the extreme variability in concentration and the wide range in contaminants present some difficulty in the design of an air stripper. The average design concentration of the various compounds was 292,980 ppb (15 compounds), and the maximum expected level was five times greater than the average. Design removal efficiency for the extraction air stripper was 96.59 percent. The extreme variability also introduces some difficulty in the design of a vapor-phase GAC absorber system. The

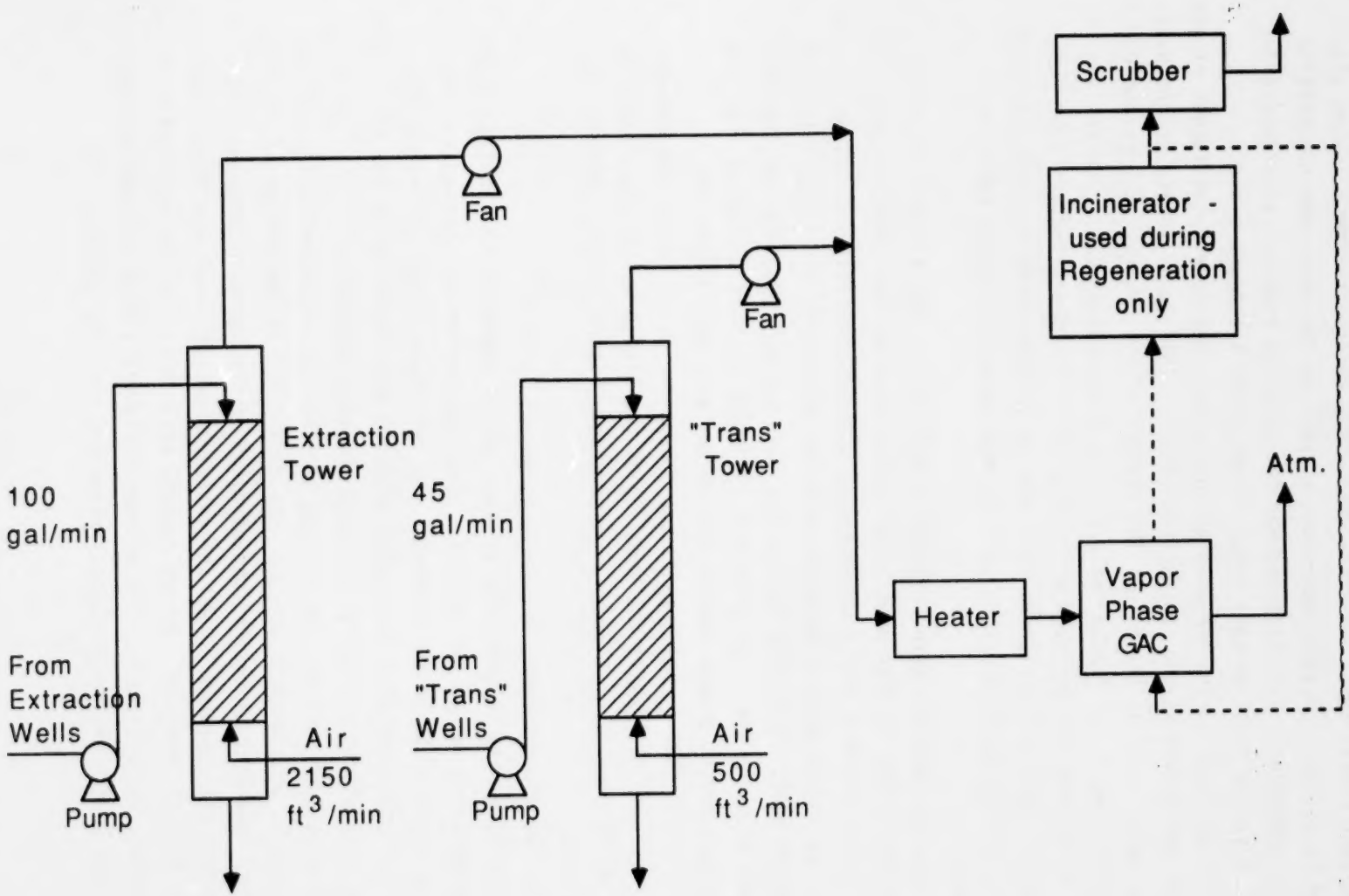

Figure 7. Process flow diagram of the CADRE system at Western Processing.

TABLE 10. SUMMARY OF SELECTED DESIGN DATA FOR WESTERN PROCESSING SITE

Number of stripper columns: 2[a]

EXTRACTION TOWER

Water volume treated: 100 gal/min (initial), 200 gal/min (maximum)
Air volume: 2150 cfm (initial), 2670 cfm (maximum)

Tower height - 26 ft
Tower diameter -40 ft
Packing height - 40.5 ft
Packing type - 2 in. Jaeger Tripack

Air/water ratio - 160 (initial), 100 (maximum) (volume basis)
Air mass velocity - 1.04 kg/m²-s (initial), 1.30 kg/m²-s (maximum)
Water mass velocity - 5.36 kg/m²-s (initial), 10.72 kg/m²-s (maximum)

CONTAMINANT LEVELS

Compound	Range, ppb
Benzene	77 to 2,200
1,2-Dichloroethane	16,000
1,1,1-Trichloroethane	100 to 340,000
1,1-Dichloroethane	320 to 33,000
Chloroform	130 to 27,000
1,1-Dichloroethylene	87[a]
trans-1,2-Dichloroethylene	390,000[a]
Ethylbenzene	32[a]
Dichloromethane	1,200 to 720,000
Fluorotrichloromethane	920[a]
Tetrachloroethylene	37 to 50
Toluene	110 to 22,000
Trichloroethylene	830 to 210,000
Vinyl chloride	360[a]

TRANS TOWER

Tower height - 28 ft
Tower diameter -2 ft
Packing height - 22.5 ft
Packing type - 2 in. Jaeger Tripack
Water volume treated: 45 gal/min (initial), 60 gal/min (maximum)
Air volume: 500 ft³/min

Air/water ratio - 83.1 (initial), 62.3 (maximum) (volume basis)
Air mass velocity - 0.97 kg/m²-s
Water mass velocity - 9.65 kg/m²-s (initial), 12.87 kg/m²-s (maximum)

(continued)

TABLE 10 (continued)

CONTAMINANT LEVELS

Chemical	Design, ppb	Actual, ppb
trans-1,2-Dichloroethylene	4,000	ND
Trichloroethylene	73	9
Vinyl chloride	270	140
Dichloromethane	140	100

Design Removal Efficiencies

Chemical	Removal efficiency, %	Effluent concentration, ppb
trans-1,2-Dichloroethylene	98.12	75
Trichloroethylene	58.90	30
Vinyl chloride	88.89	30
Dichloromethane	28.57	100

VOC Emission Controls

Vapor-phase GAC adsorption with integral incinerator for carbon regeneration and VOC destruction (Calgon CADRE).

Number of beds: 2
Bed diameter: 6 ft
Bed depth: 2 ft
Carbon weight: 7,200 lb
Carbon type: BPL
Air preheater included (indirect, natural gas-fired)
Removal efficiency: 95 percent

Date of initial operation: September 1988

[a]Two separate columns with different flow and pollutant characteristics. Air is combined with a common GAC system. Designed as extraction and trans-towers at two designated flow rates.

"trans-tower" air stripper was expected to treat water contaminated primarily with trans-1,2-dichloroethylene and containing smaller concentrations of trichloroethylene, vinyl chloride, and dichloromethane. Table 10 summarizes the design parameters for this system.

During actual operations, the contaminant concentration has been approximately 10 percent of the design levels for the 15 design compounds for the extraction tower. Weekly sampling data on the trans-tower indicate that trans-1,2-dichloroethylene has virtually disappeared. Only two compounds (vinyl chloride and tetrachloroethylene) are at or higher than their design levels. Concentrations of vinyl chloride have consistently doubled their design concentration. This is not meant to imply that many compounds are still found at substantial levels (dichloromethane and trichloroethylene are found at concentrations greater than 8000 ppb each); instead, it merely indicates that the design basis does not match the actual operation at this time. A bentonite slurry wall around the site has apparently reduced, but has not stopped contaminant migration in the ground water. Water from the treatment facility can be discharged to the local publicly owned treatment works (POTW) or returned to the site for soil flushing to assist in VOC removal.

At the time of this report, the largest loading of VOCs to the vapor-phase GAC system comes from the extraction tower; the trans-tower provides only minor amounts to the overall loading (mostly vinyl chloride). The primary water flow rate of 100 gal/min puts the extraction tower air stripper at the low end of the scale for water volume handled. The primary air/water ratio of 160:1 places the design in the upper range for air/water ratios. The level of contamination encountered, however, is the highest of all the sites included in this comparison and the high air/water ratio appears proper within this context.

The vapor-phase GAC system has posed some problems. During a regeneration cycle in January 1989 the carbon in one of the beds caught fire. The precise cause of this fire was not provided. The bed was repaired and placed back in service. Modifications made to the system at that time should prevent any recurrence of this problem. Although emission testing of the CADRE system may still be required, the performance of the vapor-phase GAC is monitored frequently by testing inlet and outlet concentrations with an

ultraviolet photoionization detector. The photoionization detector is calibrated before each inlet/outlet test by using 1,2-dichloroethylene.

Cost data were requested for this site because it represents a relatively recent installation. Cost data, however, were not available either in the files of the EPA Regional Offices or at the site itself. Thus, no comparison of cost data is possible.

3.6 HICKSVILLE MEK SPILL SITE

The Hicksville MEK Spill Site represents one of the simpler of the seven selected sites because it involves only one contaminant, methyl ethyl ketone. The air stripper at this site, however, was a different technology from that used at the other sites. It is High-Temperature Air Stripper (HTAS), in which the contaminated water is brought up to an elevated temperature before being contacted with air as in a normal stripper. The advantage of this type of system is that compounds such as some alcohols and ketones, which have relatively high vapor pressures and low Henry's Law constants, can be stripped from the water with a much smaller air stripper. In fact, tests conducted at this site indicated that a conventional column with five times the air volume of the HTAS or with substantially more packing would be required to achieve the same degree of removal as the HTAS.

The Hicksville MEK Spill Site is located in Hicksville, New York, on Long Island in Nassau County. An overturned tank truck resulted in a spill of approximately 4800 gallons of MEK. The cleanup action was initiated as an emergency removal action, limited duration ($1 million and 6 months). The total operating time for this air stripper was 125 days before the removal action was completed. The water was treated in a batch-type operation (untreated water was stored in one 6000-gal tank, and the treated water was stored in two 50000-gal tanks until tests verified that the required degree of treatment was achieved); however, the stripper ran continuously during each batch.

The HTAS concept uses a small package boiler to provide the steam required to heat the water to an elevated temperature. The incoming water is preheated by passing it through an indirect-steam heat exchanger to bring it up to operating temperature. The typical water temperature was then 180° to 195°F when it entered the stripper. The air entering the stripper was not

preheated. The contact between air and water and the heat losses that occurred through the stripper walls decreased the water temperature as it passed through the stripper. The elevated temperature also results in greater water vapor losses than encountered in traditional strippers.

One option available (but not used in this case) is the ability to use the package boiler as a VOC control device by venting the air exiting the stripper through the boiler via the primary air supply and using the boiler as a direct-flame incinerator. The addition of a high-moisture air stream such as this would decrease the boiler efficiency somewhat, would require the use of more fuel to provide the necessary heat input (the heat available from methyl ethyl ketone combustion would be negligible), and could reduce the peak flame temperature. In this case, however, the air was vented from the top of the air stripper to the atmosphere without controls. Figure 8 is a process flow diagram for the HTAS system.

The air stripper performed well during this removal action. In general, target removal levels were achieved without having to rerun batches of water. The typical operation entailed running a batch through the stripper twice. The first pass was designed to lower the VOC concentration from an estimated 15,000 ppb influent to 250 ppb effluent. The water was reheated for the second pass and the VOC concentration was lowered to less than 50 ppb. The nominal air/water ratio was approximately 200:1 for the two passes combined. The ASPEN simulation used data from only one of the two passes. The effect of the two passes was essentially the same as passing the water through the two separate air stripper columns. Table 11 summarizes the key parameters.

The water treatment rate of 100 gal/min places this air stripper on the low end of the range for air strippers, whereas the actual air/water ratio of 120 places it in the mid-range. The MEK concentration is high (15,000 ppb) and represents a highly contaminated water stream. The HTAS is a unique system for removing a compound that is usually most difficult to air-strip. Extreme fouling difficulties, however, are an example of a problem not easily modeled nor even considered by ASPEN and reflect the "other" considerations that are important to an air stripper design.

Scaling in the preheater heat exchanger due to iron oxide was a serious problem. The water contained significant quantities of iron dissolved as FeO. Passage through the air stripper at an elevated temperature caused the

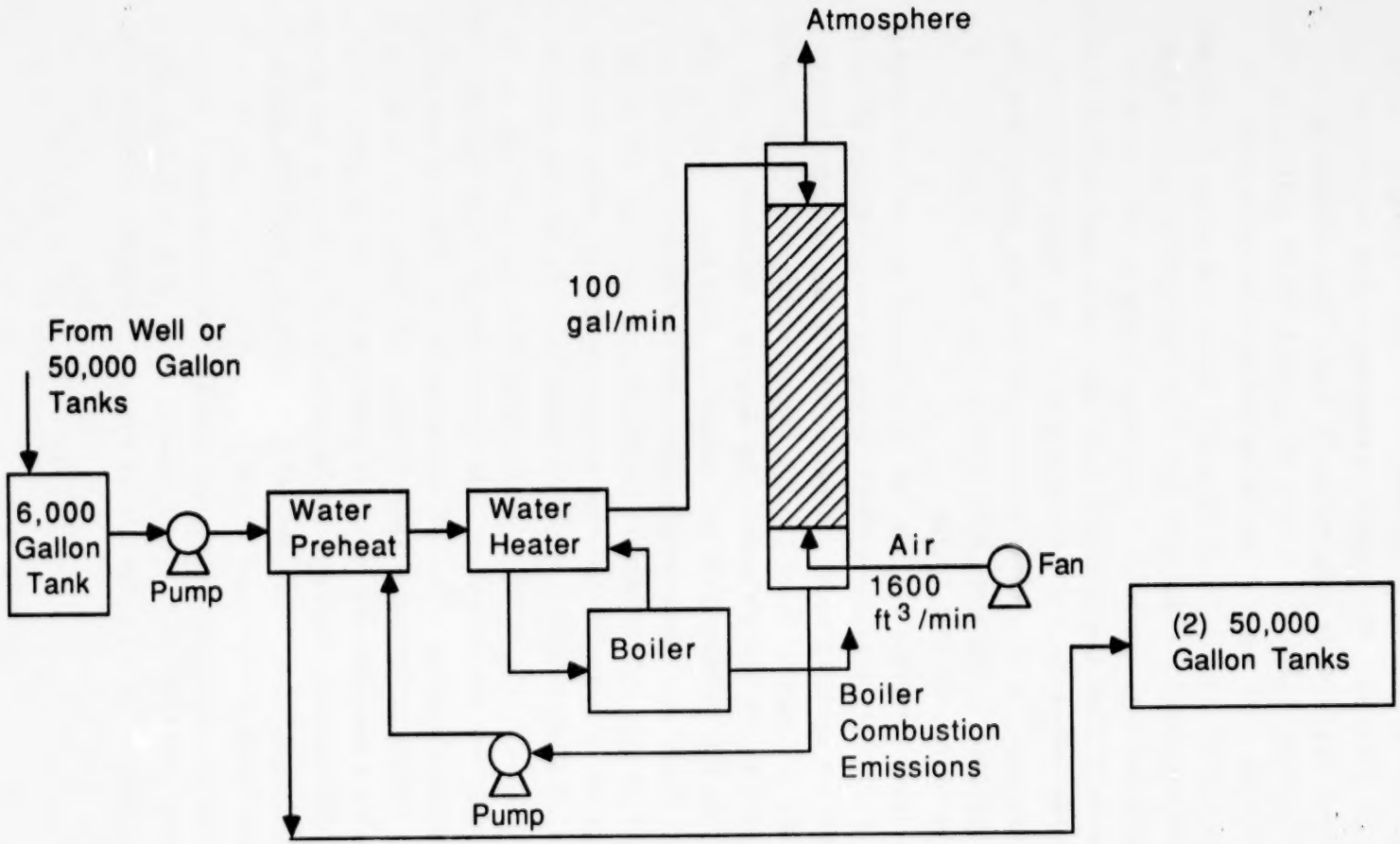

Figure 8. HTAS process flow diagram for Hicksville MEK Site.

TABLE 11. SUMMARY OF SELECTED DESIGN DATA FOR HICKSVILLE MEK SPILL SITE

Number of stripper columns: 1
Water volume treated: 100 gal/min
Air volume: 1600 cfm

Tower height - 24 ft
Tower diameter - 3.6 ft
Packing height - 15 ft
Packing type - 2 in. Jaeger Tripack

Air/water ratio - 120 (volume basis)
Air mass velocity - 0.97 kg/m²-s
Water mass velocity - 6.71 kg/m²-s

CONTAMINANT LEVELS

Chemical	Design, ppb	Actual, ppb
MEK	15,000	15,000

Designed for 98.33 percent removal of methyl ethyl ketone.

No emissions control

Date of initial operation: June[a] 1984

Note: High-Temperature Air Stripper (HTAS)

[a]Operated for 3 months for removal action.

iron to oxidize to Fe_2O_3 and to precipitate. This problem was so severe that, without some form of treatment, the heat exchanger would plug within 2 days of operation. The problem was solved by adding hydrochloric acid to lower the pH to 4.0, running the water through the HTAS, and (after achieving the desired VOC removal level) raising the pH by the addition of a sodium hydroxide solution. This substantially reduced the need to clean the heat exchanger. The Fe_2O_3, however, precipitated upon causticizing and caused problems with the reinjection of the water into wells.

3.7 GILSON ROAD (SYLVESTER'S) SITE

The seventh site included in the ASPEN performance evaluation was the Gilson Road Site (also known as Sylvester's) in Nashua, New Hampshire, in southern Hillsborough County. This site uses an HTAS to remediate contaminated ground water.

The 6-acre site was originally a sand quarry (or sand borrow pit) and then later used to dispose of both household and hazardous waste. This unapproved disposal operation began in the late 1960's. The materials included drums of waste as well as hazardous liquid chemicals and sludges that were allowed to percolate into the ground. The contamination spread through the aquifer. The total quantity of materials present could not be determined, but EPA determined from available information that more than 800,000 gallons were disposed of at the site in 1979. The site was placed on the NPL in October 1981.

Contamination in the ground water included VOCs, heavy metals, and semi- and nonvolatile organics. A single remediation technology could not handle all of these contaminants, so a treatment train was set up. The first step of the treatment removes the inorganics (metals) to prevent fouling of other equipment. The next step is the HTAS for removal of VOCs. The last step involves biological treatment. Extremely high concentrations of VOCs were found in the ground water samples (Table 12). Several of these compounds, most notably the alcohols, ketones, and tetrahydrofuran, are difficult to strip at normal temperatures. At operating temperatures of 175°F, however, the Henry's Law constants are sufficiently high to make air stripping practical with reasonable column heights and air/water ratios.

To minimize the migration of contaminated ground water, a bentonite slurry wall was installed around the site. As with many sites, after the initial operation, ground water contamination levels drop to a fraction of the design value. With the exception of 1,1,1-trichloroethane and trichloroethylene, all actual operating contaminant levels are below design values. The air stripper design was based on seven compounds, and 75 percent removal of isopropanol is the controlling compound in the design. Table 13 summarizes the design parameters for the HTAS.

TABLE 12. CONCENTRATIONS OF ORGANIC CONTAMINANTS FOUND IN THE GILSON ROAD SITE GROUND WATER

Compound	Concentration, ppb
Acetone	310,000
Benzene	3,400
Isobutanol	3,560
Chlorobenzene	1,100
Chloroform	31,000
1,1-Dichloroethane	15
1,2-Dichloroethane	18,000
Diethyl ether	20,000
Dimethyl sulfide	3,500
Ethyl benzene	1,200
Ethyl chloride	320
Ethylene chloride	73,000
Isopropanol	26,000
Methyl acetate	2,400
Methyl ethyl ketone	80,000
Methyl isobutyl ketone	21,000
Methyl methacrylate	3,500
Dichloromethane	122,500
Tetrachloroethylene	570
Tetrachloroform	1,500,000
1,1,1-Trichloroethane	2,000
1,1,2-Trichloroethane	17
Trichloroethylene	15,000
Toluene	29,000
Vinyl chloride	950
Xylenes	10,000

TABLE 13. SUMMARY OF SELECTED DESIGN DATA FOR THE GILSON ROAD SITE

Number of stripper columns: 1
Water volume treated: 300 gal/min
Air volume: 2080 cfm

Tower height - 33 ft
Tower diameter - 4 ft
Packing height - 16 ft
Packing type - 16 KOCH Type Trays @ 1 ft intervals

Air/water ratio - 51.4 (volume basis)
Air mass velocity - 1.01 kg/m^2-s
Water mass velocity - 16.08 kg/m^2-s

CONTAMINANT LEVELS

Chemical	Design, ppb	Actual, ppb
Isopropyl alcohol	36,000	532.0
Acetone	36,000	472.7
Toluene	22,000	14,884
Dichloromethane	8,300	2,365
1,1,1-Trichloroethane	430	1,340
Trichloroethylene	740	1,017
Chloroform	1,200	469

Designed for 75 percent removal of isopropyl alcohol.

Date of initial operation: June 1986

Note: HTAS design. Boiler used to heat water is also used as a direct-fired incinerator. VOC removal reported to be 99.95 percent.

Both air and water are heated in this HTAS. A heat exchanger/economizer uses the water exiting the air stripper to preheat the incoming water. The water is then heated to its operating temperature by steam provided from the boiler/fume incinerator. After the preheated water passes through the stripper, it flows through the enconomizer, and the air is sent to the boiler/fume incinerator. The boiler not only provides the steam for the HTAS and other operations around the site, but also provides a method of VOC destruction. The overall average VOC destruction is reported to be 99.95 percent, with 99.99 percent removal of tetrahydrofuran (note this is not included as one of the monitored pollutants). Emissions are exhausted from the stack along with other combustion emissions. Figure 9 is a process flow diagram for this system.

The design air/water ratio of approximately 50:1 (volume basis) is a low to moderate design value. The design water treatment rate of 300 gal/min places the stripper in the moderate size category. Unlike the other air strippers included in this study, this system uses a tray design as opposed to "conventional" packing. The use of the boiler as a fume incinerator represents a type of control not considered by the ASPEN simulation. The relatively high contamination levels and moderate air/water ratio, however, result in a relatively contaminated air stream compared with that of the other strippers in this study, and VOC controls are required.

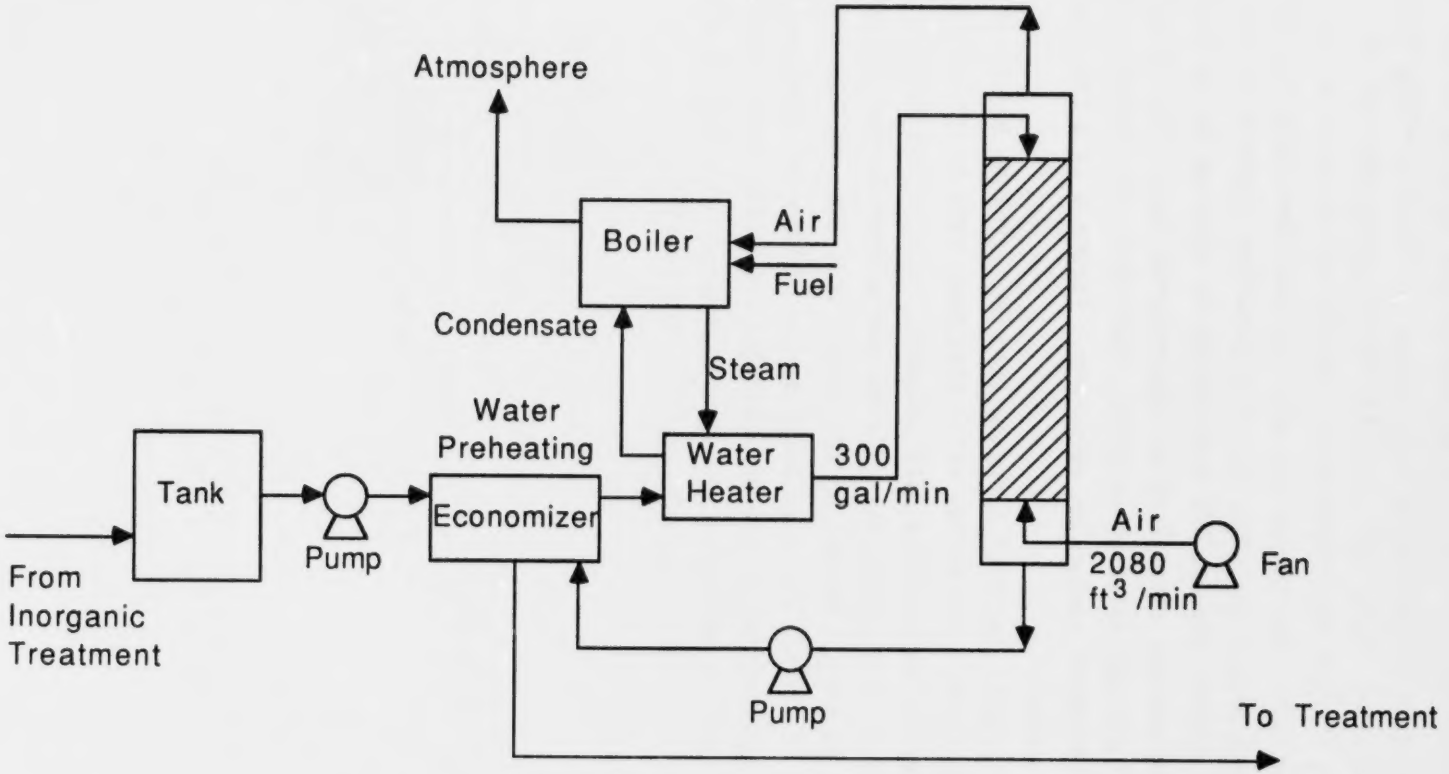

Figure 9. HTAS process flow diagram for Gilson Road Site.

SECTION 4

ASPEN SIMULATIONS AND PERFORMANCE COMPARISONS

The parameters for each of the seven sites were collected and input into the ASPEN model through the user-interface software. The design and operating parameters for each air stripper included column dimensions, packing height and types, water and air volumes treated, control device parameters, and species and influent concentrations of contaminants. Cost data were also input when available; if not, default values were used. The ASPEN air stripping program was then run in a "rating" mode to compare ASPEN's predicted results with actual performance data. Equipment and operating costs were also compared when data were available.

4.1 GENERAL RESULTS OF THE ASPEN SITE COMPARISONS

In general, ASPEN performance predictions compared quite favorably with actual performance predictions for both individual compounds at a site and with predictions of overall performance. For approximately half of the individual estimates of chemical removal, the predicted performance levels were within 1 percent of the actual performance data. In addition, the general tendency for compounds outside the 1 percent relative error band at any given site was for all the compounds either to be overpredicted or underpredicted. In other words, when the ASPEN simulations underpredicted performance by more than 1 percent relative to the actual performance data, it generally underpredicted for all compounds. Some notable exceptions to this observation are discussed in Section 4.2. Much of this tendency to overpredict or underpredict performance appears to be due to measurement or estimation inaccuracies involved with such elements as air flow measurements and temperatures or to nonideal conditions within the stripper, such as channeling (for overprediction of performance). At six of the seven sites, overall estimated performance was within 2 percent of the actual performance level, and performance was underpredicted slightly at five of these sites. Thus, it may be concluded that the ASPEN simulation tends to slightly under

predict performance. This would result in a somewhat conservative design if ASPEN were run in the "design mode" to assist in the minimum design needed for an air stripper.

Although predictions were well correlated for most cases, some compounds and designs presented a challenge to model using the ASPEN software. For example, some compounds known to be difficult to strip (e.g., acetone and methyl ethyl ketone) did not correlate well with actual performance values. Differences between actual and predicted values for another compound, dichloromethane, were also significant, with the ASPEN model overpredicting removal by a substantial margin. The cause of this large relative error could be due to sampling or analytical contamination, as dichloromethane (methlyene chloride) is a commonly used laboratory material.

A substantial relative error (compared with actual performance) occurred in the area of surrogate compounds. Although the ASPEN library of chemical properties includes nearly 400 compounds, several very important compounds, most notably cis-1,2-dichloroethylene, trans-1,2-dichloroethylene, 1,1,1-trichloroethane, and the tetrachloroethanes, are not currently included. Modeling these compounds in the simulation required the selection of a chemically similar compound. The user input program allows for the modification of the Henry's Law value as needed if the default value provided with the compound needs to be modified. For compounds such as cis-1,2-dichloroethylene or trans-1,2-dichloroethylene, for which no Henry's Law or other physical data are present in the ASPEN library, the compound 1,2-dichloroethane was selected to be the surrogate and Henry's Law is modified to reflect the dichloroethylene compound, not the dichloroethane compound. Although the two compounds are similar, the presence of double-bonded carbon atoms in the dichloroethylene compounds alter the physical behavior of the compounds in water. In general, this introduced a slightly greater relative error than would be found for the remaining compounds in the simulation at a specific site. Also, the error could be in the opposite direction of the rest of the compounds on the list. (These relative errors are discussed in Section 4.2 for the individual sites.) The use of surrogates appears to introduce a larger relative error than using the actual compound's properties when predicted performance is compared to actual reported values. The effect of any individual error on the overall

performance, however, depends on the relative error and the relative contribution of each compound to the overall influent concentration. Another problem associated with the use of surrogate compounds is that if the selected surrogate compound is also represented in the influent, it cannot be run during the simulation because only one Henry's Law value can be selected for a compound during the run. For those sites where both 1,2-dichloroethylene and 1,2-dichloroethane were found, only one or the other could be modeled per run because only the surrogate or the actual compound could be selected--not both.

Cost comparisons were available for five systems but cost data were relatively incomplete. In general, the predicted capital costs of air strippers appeared to be reasonably close to the actual capital costs when site-specific factors were considered. Operating costs reported by the sites, however, were generally lower than those predicted by ASPEN, probably because of differences in costs included (e.g., overhead and taxes) by the ASPEN cost subroutines that were not included by the various sites in their operating cost estimates. The sites generally based operating costs on capital recovery and energy-related costs.

Control equipment options at two of the sites were compared. Each site was run through the ASPEN simulation to determine the size and cost requirements for each control option (catalytic oxidation and vapor-phase GAC adsorption). The results of these simulations are discussed in Section 4.2 for each individual site.

4.2 SITE-SPECIFIC COMPARISONS

This section discusses site-specific results of the ASPEN simulations and the comparison of the ASPEN data with available actual site data. Performance ratios relative to ASPEN predictions are reported for individual compounds and overall performance. Ratios greater than 1.00 represent an under prediction by the ASPEN software when compared with actual site data. Ratios less than 1.00 represent an overprediction of performance by the ASPEN software when compared with actual site data. Where applicable, the use of surrogates is noted for individual sites, along with other assumptions or default values.

4.2.1 Tacoma Well 12A

The ASPEN library of compounds contained three of the four compounds of concern at this site. A surrogate compound was selected for the compound 1,1,2,2-tetrachloroethane and the Henry's Law constant was appropriately modified. The compound selected as a surrogate for this simulation was 1,1,2-trichloroethane. The presence of tetrachloroethylene as a compound of concern precluded its use as a surrogate although it would have been the most desirable choice. In addition, 1,2-dichloroethane was selected as a surrogate for the trans-1,2-dichloroethylene found in the contaminated water. Table 14 compares the results of the simulation with the actual performance data.

As presented in Table 14, the results for the surrogate compound for 1,1,2,2-tetrachloroethylene demonstrated a significant difference between actual and reported results. All other values were underpredicted slightly when compared with performance data. The overall results showed an approximate 2 percent difference between observed performance and predicted performance. The surrogate compound for trans-1,2-dichloroethylene provided accurate results in this case.

Because the stripper design represented five identical, parallel stripping columns, the input was set up to calculate the removal efficiency and costs for one column. The performance aspect of the model produced reasonable estimates of overall performance at the high air/water ratio. The cost comparison between the reported capital costs and the predicted costs, however, showed significant differences. The reported cost of the project was $750,000 in 1983. The estimated cost of one module (purchased equipment cost) was $236,600 (January 1986 dollars) or a total of $1,183,000 for the five modules. The total estimated capital cost for this system was $1,904,650. Even when considering the period between 1983 and 1986 during which time the inflation rate was low, the difference cannot be accounted for in the cost. The $750,000 figure was supposed to represent the total cost, including installation, engineering, and equipment cost. It actually appears, however, to be closer to the base equipment costs rather than the total system cost. The discrepancy between the two costs cannot be resolved at this time.

TABLE 14. COMPARISON OF ASPEN SIMULATION TO ACTUAL PERFORMANCE AT THE TACOMA WELL 12A SITE

Chemical contaminant	Surrogate contaminant	Influent concentration, ppb	Observed removal efficiency, %	Predicted removal efficiency, %	Comparison ratio actual/ predicted
1,1,2,2-Tetrachloroethane	1,1,2-Trichloroethane	40.9	95.00	89.17	1.07
trans-1,2-Dichloroethylene	1,2-Dichloroethane	14.3	99.99	99.98	1.00
Trichloroethylene		44.6	99.99	99.98	1.00
Tetrachloroethylene		0.9	99.99	99.98	1.00
Total VOC		100.7	97.50	95.59	1.02

4.2.2 Rockaway Township Site

All but three of the seven chemical contaminants currently found at the site are included in the ASPEN library of compounds. The three compounds not included are 1,1,1-trichloroethane, cis-1,2-dichloroethylene, and methyl-tert-butyl ether. The surrogate compounds selected to represent these compounds during the ASPEN simulation were 1,1,2-trichloroethane, 1,2-dichloroethane, and ethyl-propyl-ether, respectively. The choice of 1,1,2-trichloroethane as a surrogate for 1,1,1-trichloroethane is a good one because the two chemicals are very similar in structure and molecular weight, the Henry's Law constant has been appropriately adjusted. Ethyl-propyl ether is a less ideal choice, although it is similar in molecular weight and of the same chemical family structure. The differences in the physical characteristics are great enough that, even with the adjustment to its Henry's Law constant, some difference between actual and predicted performance would be expected. The choice of 1,2-dichloroethane as a

surrogate is a good one because its chemical structure is reasonably similar to that of cis-1,2-dichloroethylene. No 1,1-dichloroethylene was included in the run because its logical surrogate is 1,1-dichloroethane, which was already included in the chemical list.

Table 15 shows the results of the ASPEN simulation. The predicted performance and actual performance are in good agreement for most of the compounds. The predicted removal efficiency for methyl-tert-butyl ether is lower than the observed value by approximately 9 percent. The significance of this difference on overall performance is negligible because of the small contribution of methyl-tert-butyl ether to the overall VOC loading. Also, the difference in the predicted versus actual removal could be accounted for by the detection limits of the monitoring methodology. Overall, the ASPEN predictions differ slightly from predicted performance when compared with actual data. These differences are considered insignificant, however, when compared with the monitoring methodology. It should be noted that this is a high air/water ratio design (approximately 200:1).

The estimated cost for installing the air stripper system was $375,000 versus the ASPEN-predicted cost of $269,240. Extensive site preparation costs and pilot study work may account for a portion of this difference. The utility costs for the operation of the column agree quite well; the reported estimated costs were approximately $57,000, compared with the predicted $48,000. Differences between these two values, when compared on the basis of same unit cost for electricity, can be accounted for by changes in air temperature throughout the year, which changes actual energy requirements. The values input into this ASPEN simulation represent only a limited time frame, which expands to a longer time frame (i.e., one year) for operation costs. In addition, other costs, such as the use of an iron sequestering agent, are not included in the cost of operating the air stripper; however, they represent a real cost because the air stripper operation has a negative effect on the dissolved iron in the ground water.

TABLE 15. COMPARISON OF ASPEN SIMULATION TO ACTUAL PERFORMANCE AT THE ROCKAWAY TOWNSHIP SITE

Chemical contaminant	Surrogate contaminant	Influent concentration, ppb	Observed removal efficiency, %	Predicted removal efficiency, %	Comparison ratio actual/ predicted
Trichloroethylene		28.3	99.99	99.96	1.00
Methyl-tert-butyl ether	Ethyl-propyl-ether	3.2	99.99	91.56	1.09
1,1-Dichloroethylene[a]		4.0	99.99		
cis-1,2-Dichloroethylene	1,2-Dichloroethane	6.4	99.99	99.98	1.00
Chloroform		1.3	99.99	99.96	1.00
1,1,1-Trichloroethane	1,1,2-Trichloroethane	20.0	99.99	99.25	1.01
1,1-Dichloroethane		2.0	99.99	99.98	1.00
Total VOC		65.2	99.99		
		(61.2)[a]		99.29	1.01

[a]Not modeled. Predicted results do not include this compound.

4.2.3 Brewster Wellfield Site

The Brewster Wellfield Site was modeled for three compounds. A surrogate compound for 1,2-dichloroethylene (1,2-dichloroethane) was selected for the simulation, and the Henry's Law constant was modified appropriately in the data input. Table 16 shows the results for the three compounds.

The most obvious result is that performance is overpredicted somewhat for each compound. The results were closest for tetrachloroethylene and the farthest apart for trichloroethylene. The maximum relative error, however, was approximately 5 percent. Potential causes for these differences include the channeling of air or water through the air stripper, inaccuracies in estimating water temperature, inaccurate estimates of air flow through the stripper, and the sampling methodology used. Also the air/water ratio at this site is 50:1, which is the second-lowest value of the selected sites. The hypothesis is that the lower the air/water ratio, the greater the potential for nonideal effects such as channeling to occur within the stripper column. Overall, however, the predictions are within 2 percent of the overall observed VOC removal efficiency, and based on the other potential sources of error, the predicted results appear to correlate well with observed performance.

The reported installed cost for the air stripper was $138,000 versus a predicted cost of $100,000. Some of the costs attributed to the air stripper project at the Brewster Well Field are estimated from a total water project cost (i.e., a percentage of site preparation costs, piping costs, etc.). Changes in these factors would change the estimated cost. The assumptions used to generate the estimated cost are well documented.

The estimated annual costs were predicted to be $52,500/year versus the actual site-estimated costs of $26,138/year, or approximately one-half of the ASPEN-predicted cost. The largest portion of this difference is due to the length of time used for the capital cost recovery period. The data reported by the site represent a 20-year period, whereas the ASPEN prediction was based on 10 years. When the ASPEN estimate is based on a 20-year period, the predicted annual cost is $20,720, which is somewhat lower than actual estimates for the site. This variation can be attributed to the difference in initial capital costs estimated for the site.

TABLE 16. COMPARISON OF ASPEN SIMULATION TO ACTUAL PERFORMANCE AT THE BREWSTER WELL FIELD SITE

Chemical contaminant	Surrogate contaminant	Influent concentration, ppb	Observed removal efficiency, %	Predicted removal efficiency, %	Comparison ratio actual/predicted
Tetrachloroethylene		200	98.50	99.42	0.99
Trichloroethylene		30	93.33	98.67	0.95
1,2-Dichloroethylene	1,2-Dichloroethane	38	95.59	99.67	0.96
Total VOC		268	97.01	99.37	0.98

In summary, the ASPEN model overpredicted performance slightly and underestimated equipment and operating costs. Much of the difference in the values, however, can be accounted for in the assumptions inherent to data gathering; thus, for this site, the predictions appear to represent satisfactory performance and costs estimates.

4.2.4 Verona Well Field Site

The Verona Well Field Site included nine contaminants in the influent water to the air stripper. Only seven of the nine compounds were modeled because two of the compounds were not included in the ASPEN library. The two compounds not modeled were cis-1,2-dichloroethylene and 1,1-dichloroethylene. Surrogate compounds could not be selected for these two because the compounds that would normally be selected as surrogates were already included in the compound list. The surrogate compound selected for 1,1,1-trichloroethane was 1,1,2-trichloroethane. These data were input into ASPEN, and Table 17 presents the performance results.

TABLE 17. COMPARISON OF ASPEN SIMULATION TO ACTUAL PERFORMANCE AT THE VERONA WELL FIELD SITE

Chemical contaminant	Surrogate contaminant	Influent concentration, ppb	Observed removal efficiency, %	Predicted removal efficiency, %	Comparison ratio actual/ predicted
1,1-Dichloroethane		6.6	98.53	100.0	0.99
1,2-Dichloroethane		4.1	29.27	88.85	0.33
1,1,1-Trichloroethane	1,1,2-Trichloroethane	10.3	76.70	83.06	0.92
cis-1,2-Dichloroethylene[a]		15.3	83.01		
1,1-Dichloroethylene[a]		1.0	99.99		
Trichloroethylene		2.1	99.99	99.98	1.00
Tetrachloroethylene		16.4	99.99	100.00	1.00
Dichloromethane		41.2	66.26	99.14	0.67
Vinyl chloride		34.0	99.99	100.00	1.00
Total VOC		131.0	82.90		
		114.7[a]	83.32[a]	97.79[a]	0.85[a]

[a]Compounds not modeled. Results reflect performance excluding noted compounds.

The results indicate that ASPEN overpredicted performance for this case by approximately 15 percent. The compounds that account for this overprediction are 1,2-dichloroethane, dichloromethane, and the surrogate for 1,1,1-trichloroethane. The difference between the observed and predicted values for the surrogate is approximately 8 percent. The relative error for 1,2-dichloroethane and dichloromethane is substantial. The cause of this error is not readily apparent but the fact that only two compounds were affected suggests that it may be due to a sampling and measurement error (i.e., contamination of the sample) rather than a substantial problem with the ASPEN simulation. For example, the observed removal efficiency is significantly lower than would be expected for both compounds, especially 1,2-dichloroethane. Dichloromethane (methylene chloride) is a common laboratory solvent and could be a source of sample contamination. As the air/water ratio decreases the various nonideal factors (such as channeling or poor water distribution) may be more important in actual performance than can be modeled. This possible source of overprediction would be less likely to cause a problem at higher air/water ratios. The Verona Well Field air stripper represents the lowest air/water ratio (20:1) of the seven selected sites.

The air emissions from the stripper pass through a vapor-phase GAC adsorber system for control of VOCs. This was included in the cost of the total system, which and was estimated to be $675,000. The ASPEN prediction for the air stripper/carbon adsorber system cost was $514,000, which is lower than the reported value by 24 percent. In addition, the vapor-phase carbon adsorption system actually operated as a nonregenerative system rather than a steam-regenerable system. This, of course, would affect the cost of operation. The reported cost of operation and maintenance was $223,000 including capital-recovery costs. The ASPEN predictions were much lower ($185,300), partially because of the use of steam regeneration rather than carbon replacement and offsite regeneration.

Initial testing data from the Verona Well Field indicated that performance of the vapor-phase GAC system was quite good, despite the extremely dilute concentrations of the contaminants in the gas stream. As would be expected, the lighter-molecular-weight compounds broke through the carbon first because the adsorption capacity varies with concentration and

molecular weight. Based on this initial evaluation, it appeared that a carbon change-out every year (12 months), as initially planned, was going to be normal routine. When the additional contamination of the highly contaminated zone was added to the normal well field contaminants, however, "normal" contaminant concentrations doubled (sometimes tripled). In addition, two compounds not normally seen at the air stripper, vinyl chloride and dichloromethane, were added in substantial quantities, as the adsorption capacity of the liquid-phase treatment system used before the air stripper was limited for these compounds.

The inlet and outlet concentrations of the vapor-phase GAC system were not routinely checked, however, under the interim removal action, the system was tested on a more frequent basis to determine if changeout was needed. During a test conducted in April 1987, both inlet and outlet concentrations were measured. Some pollutant concentrations fell below the detection limits of the test method. Table 18 summarizes the data on the water and air concentrations for this system. Several items from these test data are worth noting with regard to vapor-phase GAC performance. First, despite the increased water concentrations, the test method determined that inlet VOC concentrations in the gas were very dilute. Second, the overall removal efficiency is quite low (12.8%) because the two most prevalent compounds at the inlet are also found at the outlet. Finally, the outlet concentration of dichloromethane is much greater than the inlet concentration, which suggests that the vapor-phase carbon was saturated with VOCs. The data suggest that vinyl chloride was being controlled only slightly and that dichloromethane was being desorbed at a rate nearly equal to the inlet, which resulted in an emission rate higher than if it were not controlled at all. Such situations must be accounted for in the design of carbon adsorbers, because competitive adsorption/desorption will occur when multiple compounds are involved. Other data provided from a test conducted 2 months later suggest the performance had improved, but some of the test data were inconsistent in that the water and air sample VOC concentrations did not match well.

The estimated once-a-year carbon change-outs were substantially increased to once every 4 to 6 months, usually as a result of testing. Under normal circumstances, when concentrations of various contaminants are relatively steady, the operating characteristics and time before VOC

TABLE 18. SUMMARY OF INLET AND OUTLET CONCENTRATIONS AND COLLECTION EFFICIENCIES FOR SELECTED COMPOUNDS, APRIL 30, 1987

Chemical	Air stripper			GAC adsorption system				
	Influent, µg/liter	Effluent, µg/liter	Removal efficiency, %	Inlet, µg/m³	Outlet east, µg/m³	Removal efficiency, %	Outlet west, µg/m³	Removal efficiency, %
1,1-Dichloroethane	6.6	0.5	92.42	101	ND[a]	99.99	ND	99.99
1,2-Dichloroethane	4.1	2.9	29.27	8.7	ND	99.99	ND	99.99
1,1-Dichloroethene	1.0	ND	99.99	BDL[b]				
cis-1,2-Dichloroethene	15.3	2.6	83.01	BDL				
Dichloromethane	41.2	13.9	66.26	197	330	-67.51	323	-63.96
Tetrachloroethene	16.4	ND	99.99	37.4	ND	99.99	ND	
1,1,1-Trichloroethane	10.3	2.4	76.70	BDL				
Trichloroethene	2.1	ND	99.99	BDL				
Vinyl chloride	34.0	ND	99.99	162	131	19.14	116	28.40
Total	131.0	22.4	82.90	516.1	461	10.68	439	14.94

[a]None detected.

[b]Below detection limit.

breakthrough may be well defined and require little if any monitoring. When variations from the normal condition occur and extreme variability is the norm, routine and frequent monitoring should be required.

One option available for evaluating GAC designs is to determine if breakthrough would be allowable for certain difficult-to-adsorb compounds and to run the simulation without including them in the chemical compound list. This would determine how much of a change occurs in VOC control equipment size and cost occurs as a result of allowing certain compounds to pass through uncontrolled. This was not done for the performance comparison, but the results could be used to evaluate different designs.

4.2.5 Western Processing Site

The Western Processing Site was the most complex site to evaluate because it involved numerous compounds. Of the 22 VOCs tested for in the ground water, 18 had measured concentrations above the detection limits. Fourteen of these 18 compounds were modeled by the ASPEN model. The four compounds not modeled were hexachlorobutadiene, hexachloroethane, nitrobenzene, and 1,1,2-trichloroethane. With the exception of 1,1,2-trichloroethane, none of these compounds is currently included in the ASPEN library. The concentrations of these compounds, however, were minor compared with concentrations of other compounds. Only one surrogate compound was needed for this simulation (1,1,2-trichloroethane was substituted for 1,1,1-trichloroethane).

Table 19 presents a comparison of ASPEN simulations and actual performance results at the Western Processing Site. With several notable exceptions, the predicted removal efficiency was greater than the observed removal efficiency. In most instances, the difference between the actual and predicted values was within a 2 percent relative error. The difference for benzene was greater, approximately a 7 percent relative error. Two other compounds, 1,2-dichloroethane and 1,2-dichlorobenzene, displayed large differences between the observed and the predicted values. No reason for these discrepancies was apparent but the values suggest either a sample testing problem or the need to select a smaller Henry's Law constant.

Two compounds, carbon tetrachloride and isobutanol, showed a ratio of zero between the ASPEN run and the actual performance. In the case of carbon tetrachloride, the test method indicated an inlet concentration of 5 ppb

TABLE 19. COMPARISON OF ASPEN SIMULATION WITH ACTUAL PERFORMANCE AT THE WESTERN PROCESSING SITE

Chemical contaminant	Surrogate contaminant	Influent concentration, ppb	Observed removal efficiency, %	Predicted removal efficiency, %	Comparison ratio actual/ predicted
Benzene		73	93.15	99.95	0.93
Carbon tetrachloride		5		99.97	0.00
Chloroform		781	99.36	99.95	0.99
1,2-Dichloroethane		22	77.27	99.63	0.78
1,1-Dichloroethylene		89	94.38	99.98	0.94
1,1,1-Trichloroethane	1,1,2-Trichloroethane	1,440	99.65	98.12	1.02
Trichloroethylene		8,220	99.94	99.96	1.00
Vinyl chloride		159	99.37	99.99	0.99
Dichloromethane		8,170	99.63	99.97	1.00
Tetrachloroethylene		378	98.68	99.96	0.99
Toluene		551	99.09	99.93	0.99
1,2-Dichlorobenzene		11	54.55	99.52	0.55
Isobutylalcohol		10	0.00	3.25	0.00
Methyl ethyl ketone		1,480	70.27	48.17	1.46
Total VOC		21,389	97.52	96.21	1.01

and an outlet concentration of less than 5 ppb without specifying the concentration. Carbon tetrachloride would be expected to be stripped from the water at high efficiency, and this result appears to be caused by the testing methodology. Its effect on the overall results is very small. For isobutanol, the difference between the observed removal efficiency of essentially zero percent and the predicted efficiency of 3.25 percent is not significant and can be considered to be accurate.

The removal efficiency for two of the compounds, 1,1,1-trichloroethane (using the surrogate) and methyl ethyl ketone, was underpredicted by ASPEN. The error in the use of the surrogate produced only a 2 percent relative error for 1,1,1-trichloroethane and, therefore, is considered to correlate well with actual performance. Methyl ethyl ketone removal efficiency was significantly underpredicted by ASPEN (by approximately 46%). Actual removal efficiency for methyl ethyl ketone was reported to be 70.27 percent versus the 48.17 percent predicted by ASPEN. Although methyl ethyl ketone is a particularly difficult compound to remove (as evidenced by its low Henry's Law constant), there are no apparent reasons for this value to be significantly different from the predicted value, as sample contamination would not normally cause this type of discrepancy. For the moment, this variation remains an unexplained anomaly. The error is significant because methyl ethyl ketone represents an important contributor to overall contaminant levels. When combined with the effects of the surrogate used for 1,1,1-trichloroethane, they offset the slight overpredictions for the remaining compounds.

As was the case at the Verona Well Field Site, VOC emissions are controlled with a vapor-phase GAC adsorption system. The system is not steam-regenerated, but uses an incinerator to provide hot gas for regeneration. Capital cost data for this system and its associated operating costs were not available for comparison with ASPEN simulation values. These costs may not be directly comparable in this case because of regeneration differences.

PEI reviewed the data from both the inlet and outlet tests conducted at the vapor-phase GAC adsorption system. These inlet and outlet tests were conducted with a photoionization type detector calibrated by using a known concentration of 1,2-dichloroethylene in a carrier gas. Such checks are

typically conducted every 4 hours. PEI examined daily average inlet and outlet concentrations for a 26 day period in the spring of 1989. Daily average removal efficiencies ranged from a low of 17.4 percent to a high of 70.6 percent. The average for this period was 50.2 percent removal, which is far below the design value of 95 percent.

The photoionization detector cannot determine which compounds are present in the gas stream. The ultraviolet lamp used must be of sufficient strength to photoionize all of the VOCs of interest; otherwise, VOCs could be present but not detected. For example, detection of dichloromethane requires a very-high-intensity lamp. Further, it cannot be assumed that the fractional compositions of the chemicals in the air stream are identical between the inlet and outlet. Most likely they are not, as was demonstrated at the Verona Well Field Site. One problem noted with the testing of the vapor-phase GAC system is the missing mass of VOCs not found during testing of the inlet. Although considerable variability was observed in the readings that made up the daily averages, they were always considerably less than what would have been expected from a mass balance. The photoionization detector may not have the proper bulb installed, which would make it impossible for the detector to "see" compounds such as dichloromethane. Also, some dilution of the gas stream might be occurring as a result of the "trans-" stripper. In any event, limited test data from the site seems to indicate that performance is significantly below design values.

4.2.6 Hicksville MEK Spill Site

The use of a high temperature to remove methyl ethyl ketone presents a unique problem to the air stripper model. The ASPEN software automatically adjusts the Henry's Law constant for water temperature for the compounds; thus, increases or decreases are automatically computed for most design situations. The Onda-correlation, however, has a temperature limit of 45°C in its estimation of mass transfer coefficients. The program assumes that any temperature above this limit is 45°C. The "true" mass transfer coefficient is likely to be different from that predicted by the Onda-correlation, and the only method of compensating for this limitation is to alter the apparent Henry's Law constant for the compound.

The presence of only one compound in the water allowed for the altering of the Henry's Law constant to match the performance observed for this

stripper design. A good match between predicted and actual performance was obtained by changing the constant from a literature value of 4.35×10^{-5} atm-m^3/mole to 1.25×10^{-4} atm-m^3/mole. At this Henry's Law value, the predicted removal efficiency was a 96.79 percent (Table 20) versus an observed value of 98.41 percent.

The application of HTAS would probably be limited to cases where difficult-to-strip compounds are encountered in significant quantities. For compounds with Henry's Law constants greater than 10^{-4} atm-m^3/mole, a correction to the Henry's Law constant is probably not necessary to compensate for the temperature limitation of the calculation of mass transfer coefficients.

The predicted installed cost of the air stripper was $212,000 versus the reported cost of $323,000. The reported total cost, however, also included an auxiliary package boiler and tank arrangement that could not be included in the ASPEN simulation. When this is considered, the ASPEN cost predictions should compare well with the actual cost of the air stripper for this site. Much of the operating cost associated with this stripper involved the combustion of fuel oil to heat the water for stripper operation.

The ASPEN model could not predict the problems associated with iron oxide in the water or the costs associated with correcting these problems (acidification and neutralization). Therefore although the model is an important tool for predicting the removal efficiency for VOCs, other important water-quality parameters cannot be ignored.

4.2.7 Sylvester's Gilson Road Site

The Gilson Road Site uses a HTAS to remove isopropyl alcohol, acetone, and other compounds from the contaminated ground water. As at previous sites 1,1,2-trichloroethane was selected as a surrogate for 1,1,1-trichloroethane, and an appropriate adjustment was made to the Henry's Law constant of the surrogate. All other compounds were selected with the default values for Henry's Law constant for each compound.

Table 21 summarizes the observed and predicted performance for each compound. For all compounds except acetone, the model slightly over-predicted results when compared with actual performance data. The model predicted nearly complete removal, whereas the observed performance suggested

TABLE 20. COMPARISON OF ASPEN SIMULATION WITH ACTUAL PERFORMANCE AT THE HICKSVILLE MEK SPILL SITE

Chemical contaminant	Surrogate contaminant	Influent concentration, ppb	Observed removal efficiency, %	Predicted removal efficiency, %	Comparison ratio actual/ predicted
Methyl ethyl ketone		15,000	98.41	96.79	1.02

TABLE 21. COMPARISON OF ASPEN SIMULATION WITH ACTUAL PERFORMANCE AT THE SYLVESTER'S GILSON ROAD SITE

Chemical contaminant	Surrogate contaminant	Influent concentration, ppb	Observed removal efficiency, %	Predicted removal efficiency, %	Comparison ratio actual/ predicted
Isopropyl alcohol		532	95.30	99.08	0.96
Acetone		473	91.93	59.99	1.53
Toluene		14,884	99.87	100.00	1.00
Dichloro-methane		236	93.79	100.00	0.94
1,1,1-Tri-chloroethane	1,1,2-Tri-chloroethane	1,340	99.45	100.00	0.99
Trichloro-ethylene		1,017	99.71	100.00	1.00
Chloroform		469	99.06	100.00	0.99
Total VOC		18,951	99.41	99.00	1.00

a slightly lower removal efficiency. The overpredictions of performance were greatest for isopropyl alcohol and dichloromethane. Some of this overprediction may be the result of nonideal conditions not fully accounted for by the model. This stripper differs from those at other sites, not only because of its operating temperature, but also because it uses trays instead of packing to obtain the mass transfer from liquid to gas.

The performance of the stripper with respect to acetone indicated a large difference between the actual and predicted removal efficiencies; actual removal efficiency was underpredicted by approximately 56 percent. Of the compounds on the list for this site, acetone was the most difficult to strip, with a Henry's Law constant of 2.50×10^{-5} atm-m^3/mole. As was the case for the Hicksville MEK Spill site, the use of the HTAS presents some computational difficulties for the ASPEN model because of the temperature limitations on the Onda-correlation method of calculating mass transfer coefficients. It may be prudent to increase the effective Henry's Law constant by approximately one-half to one order of magnitude for this compound and other compounds with values less than 10^{-5} atm-m^3/mole to overcome the temperature limitations imposed by the model.

The cost of the stripper reported by the operation was $45,000. This represents base equipment cost, not installed capital cost. This correlates well with the value of $50,600 predicted by ASPEN. Because this stripper also includes a boiler to provide steam for the stripper and other remedial processes on site, the installed cost would be substantially more than predicted by ASPEN. The actual annual cost would also be greater.

4.3 SUMMARY

The ASPEN performance predictions generally correlated well with observed performance and provided estimates that were within 2 percent of the observed removal efficiency. The use of surrogate compounds generally introduced a larger error than was observed for the actual compounds at a given site. This is believed to be due to the fact that although chemically similar, the physical data from the ASPEN library that was used in computing mass transfer coefficients were sufficiently different to introduce larger errors in the predicted efficiency. The effect of these errors depends on the fractional composition of the total VOC loading of the surrogate

compound. With the exception of the surrogate compounds and some isolated chemicals, the ASPEN predictions tended either to over- or underpredict for all compounds at a particular site.

Two compounds (1,2-dichloroethane and dichloromethane) presented a problem with regard to calculating removal efficiency. Part of the problem with dichloromethane could be explained by sampling errors; however, 1,2-dichloroethane seemed to present a problem whether it was a surrogate or not. Ketones, notably methyl ethyl ketone and acetone, also may present a problem, but these compounds were encountered in only one conventional air stripper, and a great discrepancy occurred in predicted versus observed performance. The use of a HTAS represents a special case in which temperature limitations in the calculation of mass transfer coefficients may require a change in the Henry's Law constant used to estimate removal efficiency.

Based on this limited data set, it appears that at lower air/water ratios the ASPEN model may slightly overpredict performance, and at higher air/water ratios it may slightly underpredict performance. Although data are limited, this result is not unexpected because nonideal factors may have a more detrimental effect on performance at lower air/water ratios than at higher ratios (e.g., greater than 50:1).

In both cases where vapor-phase GAC adsorption was used, the ASPEN model predicted that a much greater quantity of carbon was needed to ensure good performance. Test data available from both sites indicated that actual performance was much lower than design performance. The presence of compounds such as vinyl chloride and dichloromethane greatly increases the carbon requirements of the adsorber, which suggests that another alternative may be appropriate for application where these compounds are found.

Cost comparisons were limited by available site data. In general, site-specific factors and lack of itemized costs from the sites limited the ability to compare cost data. In some cases, the predicted costs appeared to be reasonably close to reported costs. More information is needed to make more definitive comparisons.

SECTION 5

EMISSIONS TRADEOFFS FROM AIR STRIPPERS

Air stripping, by design, transfers VOC's from water to air according to physical laws defined by equilibrium relationships, diffusion, and mass transfer. Often, the focus is on the removal of the VOC from the water and the achievement of target concentrations after the water passes through the stripper. This focus tends to overshadow other aspects of the stripper operation.

Four of the seven sites included in the performance comparison are not equipped with VOC emission controls. In the future, more air strippers will likely be equipped with some form of VOC emission control. These may be required by air toxic regulations that are Applicable or Relevant and Appropriate Requirements (ARARs) for Superfund sites or under other guidelines or directives. The application of VOC emissions control, however, is not without its costs or impacts. Discussions regarding the application of a system to remove or control VOC emissions tend to focus on the cost of the equipment and its performance.

The specification and installation of VOC controls will probably change the design of air strippers. For example, early designs of air strippers tended to rely on large air/water ratios to remove VOCs from contaminated water. This usually meant that large quantities of air had to be moved through the system to produce very dilute VOC-bearing gas streams. Application of VOC controls to these systems tended to require large and expensive control systems because much of the sizing of equipment has a direct relationship to gas volume handled. The sizing of catalytic oxidizers is also directly influenced by the amount of gas handled because this influences both incinerator size and fuel requirements. Vapor-phase GAC adsorption systems have limits on the velocity and pressure drop through a carbon bed that need to be considered in addition to the amount of carbon required for the quantity and concentration of the VOCs in the gas stream. In either case, a reduction in gas volume through a reduction of the

air/water ratio will generally result in a more cost-efficient control system.

The operation of any air-stripping system generates the potential for air emissions. Most apparent are the uncontrolled VOC emissions from the stripper itself. The operation of the stripper, however, requires the use of pumps and fans to move water and air and energy (electricity) to operate this equipment. Although electricity may not be generated on site, some incremental increase in electrical generation and the amount of fuel combusted at a generating station is required to produce this energy, and this results in some incremental increase in emissions of NO_x, SO_2, CO, particulates (PM_{10}), and nonmethane hydrocarbons. Generally, the quantity of electrical energy used is small compared with the output of a single generating station. Also, the impact of this generation remote from the site of the air stripper is not considered. Although this impact is real, it is incrementally small.

A more direct local impact should be considered when VOC controls are applied to air strippers. Both control options (catalytic oxidation and vapor-phase GAC adsorption) require the combustion of fuel, which usually results in a local impact of greater concern than electrical consumption. Catalytic oxidation, for example, requires fuel combustion to establish and maintain the incinerator temperature for VOC destruction. This fuel combustion produces SO_2, NO_x, CO, and nonmethane hydrocarbons. In addition, the presence of halogenated VOCs produces halogenated acids (HX) upon combustion, which also must be considered. Vapor-phase GAC adsorption also generates emissions. The model assumes steam regeneration of the carbon and the use of a small boiler to produce the needed steam. The combustion of No. 2 fuel oil to generate this steam produces the same types of pollutants as the catalytic oxidizer with one exception. The organic constituents captured by the carbon are assumed to be recovered, stored, and shipped offsite for further processing (e.g., solvent recovery). The aqueous material from steam regeneration would be contaminated with the same VOCs, and this material is assumed to be processed by the air stripper prior to its discharge. No HX are assumed to be formed because this option does not involve the combustion of halegenated VOC streams.

Offsite regeneration does not mean that no emissions are created; it only means that they are not created on site. Depending on the regeneration method used, the emissions could be nearly identical in either option (incineration or steam regeneration). For the purpose of this evaluation, offsite regeneration is assumed to be equivalent to onsite steam regeneration.

Both options also contribute to the production of carbon dioxide (CO_2) as a result of fuel combustion. Although not considered a pollutant, CO_2 is becoming more important from a global warming perspective. The quantity of CO_2 is displayed for information purposes in the ASPEN simulation results.

5.1 EMISSIONS ESTIMATE METHODOLOGY

The estimation of the uncontrolled VOC emissions rate is a straightforward material balance. The quantity of VOCs in the influent water is a known quantity that must be input as part of the initial input data. After calculating removal efficiency, the ASPEN model assumes that the VOCs stripped from the water enter the air stream. The quantity of each compound stripped from the water is summed to give the overall uncontrolled VOC emission rate.

Estimating air emissions from the control options is somewhat more complex because estimates have to be made for the average fuel consumption (10^6 Btu/h) required to operate the process. Emission factors from AP-42[2] are then used to convert fuel use to emission rates for each of the fuel combustion pollutants. The emission factors used are shown in Table 22.

The catalytic oxidation option estimates the amount of fuel required to heat and maintain the air temperature at approximately 700°F. The fuel is assumed to be natural gas. The heat requirement from this estimate is used to estimate the quantity of fuel combustion products and pollutants. The quantity of products of the combustion from the VOCs exiting the stripper is calculated and added to the fuel combustion products. Halogenated compounds are assumed to convert to HX and are summed for all halogenated compounds. The total quantity of pollutants generated from the catalytic oxidizer (except CO_2) are summed and then compared with the uncontrolled emission rates to determine if a net increase or decrease in pollutants occurred as a result of using the control equipment.

TABLE 22. EMISSION FACTORS USED BY ASPEN MODEL FOR FUEL COMBUSTION EMISSIONS[a]

Pollutant	Natural gas		Distillate oil	
	lb/10^6 ft^3	lb/10^6 Btu[b]	lb/10^3 gal	lb/10^6 Btu[c]
SO_2	0.6	6.00×10^{-4}	142(S)	1.022(S)
NO_x	100.0	0.100	20	0.144
CO	20.0	0.020	5	0.036
VOC (nonmethane)	5.3	5.30×10^{-3}	0.34	0.002
CO_2	116,596.0	116.36	22,747.0	163.65

[a]From AP-42, Supplement 13.

[b]Assumes natural gas heat content of 998 Btu/ft^3.

[c]Assumes distillate oil heat content of 139,000 Btu/gal.

The vapor-phase GAC adsorption option uses a similar approach to that of catalytic oxidation because fuel combustion emissions are estimated from heat input estimates. To estimate the heat input for the regeneration of the carbon, either the actual carbon used (rating mode) or the carbon required (design mode) is used to estimate steam requirements, given the adsorption cycle time. This, in turn, gives the number of regeneration cycles and an assumed value of 3.5 lb steam/lb carbon required to regenerate the carbon. The heat input is then estimated from the total quantity of steam required per year and averaged to a 10^6 Btu/h heat input value. The emission factors from Table 22 were then applied and summed for comparison in a manner similar to that for catalytic oxidation.

The comparison between uncontrolled VOC emissions and emissions produced as a result of using a control option resembles a comparison between dissimilar pollutants with different air toxics implications. The intent of the comparison, however, is to demonstrate that the use of air emission controls may have other impacts. In fact, the air emissions from the vapor-phase carbon adsorption may underestimate the true magnitude of

short-term impacts. Because the boiler operation may be intermittent, the values shown represent long-term averages, not short-term peak values.

5.2 EMISSIONS COMPARISONS FOR THE CONTROL OPTIONS

The data from the seven selected sites were used as a basis for emission estimates for three scenarios: no controls, vapor-phase GAC adsorption, and catalytic oxidation. Each site was run in the design mode to determine what emissions would occur given the air stripper performance and allowing the ASPEN software to estimate control equipment sizing for the two control options. The emission rates for each site are based on this design mode value.

5.2.1 Tacoma Well 12A

The selection of either option for this site results in a net emissions increase from the operation of the control equipment (Table 23). The increase in emissions resulting from the vapor-phase GAC system, however, is much smaller than that resulting from the catalytic oxidizer. This difference is caused by the large gas flow from this stripper design, because a large quantity of heat is required to bring the gas stream up to temperature. The vapor-phase option has a much lower overall impact because each of the compounds included in the contaminant list is very easy to adsorb, and the limiting factor for the GAC design is gas velocity through the beds, not a large carbon requirement.

5.2.2 Rockaway Township

No comparison could be performed for this site because of missing data in the ASPEN library for the surrogate compound ethyl-propyl ether. Computer runs gave invalid results, which are not included in the simulation.

5.2.3 Brewster Wellfield

The selection of a vapor-phase GAC adsorption system resulted in a much higher net emission increase when compared with emissions from catalytic oxidation (Table 24). Although the air/water ratio for this stripper is relatively low, the presence of two difficult-to-adsorb compounds (vinyl chloride and the surrogate 1,2-dichloroethane) increases the carbon requirements substantially. This directly affects the steam and heat input

TABLE 23. EMISSIONS COMPARISON FOR THE TACOMA WELL 12A SITE

Pollutant	No controls, kg/h	Vapor-phase GAC, kg/h	Catalytic oxidation, kg/h
Uncontrolled VOC emissions	0.0765		
HX			0.0651
SO_2		0.3785	0.8905
NO^x		0.0533	6.050
CO^x		0.0133	1.216
VOC (nonmethane)		0.0007	0.3159
CO_2		60.60	7035
Emissions from control option (excluding CO_2)		0.4459	8.5350
Net emissions decrease[a] (excluding CO_2)		-0.3694	-8.4600

[a]Negative values indicate an overall emissions increase over the uncontrolled option. Positive values indicate a net decrease.

TABLE 24. EMISSIONS COMPARISON FOR THE BREWSTER WELL FIELD SITE

Pollutant	No controls, kg/h	Vapor-phase GAC, kg/h	Catalytic oxidation, kg/h
Uncontrolled VOC emissions	0.0183		
HX			0.016
SO_2		31.79	0.005
NO^x		4.479	0.033
CO^x		1.120	0.007
VOC (nonmethane)		0.062	0.002
CO_2		5090	38.46
Emissions from control option (excluding CO_2)		37.45	0.062
Net emissions decrease[a] (excluding CO_2)		-37.43	-0.044

[a]Negative values indicate an overall emissions increase over the uncontrolled option. Positive values indicate a net decrease.

requirements, which are reflected by the pollutant emission rate. According to the ASPEN prediction, selection of the vapor-phase GAC system would significantly increase SO_2 and NO_x emissions. The GAC system boiler would be classified as a major SO_2 source under Prevention of Significant Deterioration (PSD) review.

5.2.4 Verona Well Field

Table 25 shows the results of emissions estimated for the Verona Well Field. Although this site has a vapor-phase GAC system installed, the data available on its performance suggested that its performance was poor, given the compounds it was trying to control. The ASPEN design suggested a much larger GAC system would be required, this larger system is reflected in Table 26. The presence of compounds such as 1,2-dichloroethane, dichloromethane, and vinyl chloride greatly increased carbon requirements for proper operation. Thus, although the low air/water ratio helps in the design of the catalytic oxidizer, it does little to help reduce the estimated emissions from the GAC system because of the poor adsorbability of the compounds mentioned in the preceding sentences. For such a small removal rate, the use of GAC extracts a significant emissions penalty in this case. In addition, it would be subject to PSD review because it would be classified as a major SO_2 source.

5.2.5 Western Processing Site

The emission rate comparisons for this site show some astounding numbers (Table 26). The emission rate estimates are orders of magnitude greater than all other estimates. In addition, the heat input rates required to produce these emission rates are extremely high (to put this into context, the necessary heat input rate would represent a substantial portion, approximately 2.38 million MW, of the U.S. steam-generating capacity for generating electricity). This example demonstrates that one should carefully examine the results.

In this case, the extremely large numbers are caused by the presence of large quantities of difficult-to-absorb compounds. The two compounds that have the greatest effect on the report values are vinyl chloride and dichloromethane, both of which require extremely large quantities of activated carbon to control. This further suggests that vapor-phase GAC

TABLE 25. EMISSIONS COMPARISON FOR THE VERONA WELL FIELD SITE

Pollutant	No controls, kg/h	Vapor-phase GAC, kg/h	Catalytic oxidation, kg/h
Uncontrolled VOC emissions	0.050		
HX			0.038
SO_2		146.10	0.030
NO^x		20.59	0.195
CO		5.147	0.039
VOC (nonmethane)		0.286	0.010
CO_2		23,400	226.5
Emissions from control option (excluding CO_2)		172.1	0.312
Net emissions decrease[a] (excluding CO_2)		-172.1	-0.262

[a]Negative values indicate an overall emissions increase over the uncontrolled option. Positive values indicate a net decrease.

TABLE 26. EMISSIONS COMPARISON FOR THE WESTERN PROCESSING SITE

Pollutant	No controls, kg/h	Vapor-phase GAC, kg/h	Catalytic oxidation, kg/h
Uncontrolled VOC emissions	0.355		
HX			0.280
SO_2		1.160×10^7	0.012
NO^x		1.634×10^6	0.083
CO		4.085×10^5	0.167
VOC (nonmethane)		2.269×10^4	0.004
CO_2		1.857×10^9	96.72
Emissions from control option (excluding CO_2)		1.366×10^7	0.396
Net emissions decrease[a] (excluding CO_2)		-1.366×10^7	-0.041

[a]Negative values indicate an overall emissions increase over the uncontrolled option. Positive values indicate a net decrease.

adsorption is an inappropriate VOC control method, at least for these compounds.

By comparison, catalytic oxidation looks very attractive on an overall emissions basis. A slight emission increase of approximately 11.5 percent over the uncontrolled levels is predicted for this option. The low gas volumes help to reduce the net emission increase.

5.2.6 Hicksville MEK Spill Site

The Hicksville MEK Site represented one of two cases where a net reduction of emissions resulted from the addition of controls. In this case, a net reduction occurred with the use of catalytic oxidation. This reduction was due in part to low gas volumes and high gas-stream temperatures. The carbon adsorber option indicated a net increase in emissions, although only one compound was present. Table 27 shows the results of the comparison.

Methyl ethyl ketone is a relatively easy but dangerous compound to adsorb. The heat release rates from the adsorption process can be so high that fires can occur within the carbon bed if special precautions are not taken. This generally involves humidification of the gas stream to carry away the heat of adsorption. The model does not consider this problem in its evaluation of adsorber designs.

The use of HTAS involves the use of a boiler to increase water temperature. The fuel required would likely cause a further net increase in emissions for both options. This design, however, also offers the opportunity to use the boiler as an incinerator, which reduces the supplementary fuel requirements for a separate catalytic oxidizer.

5.2.7 Sylvester's Gilson Road Site

This site was the only other site of the seven where a net reduction of emissions was predicted for one of the control options. As at the Hicksville MEK Spill Site, the catalytic oxidation option provided a net reduction in emissions due, in part, to the operation of the HTAS. A substantial increase in emissions was predicted with the use of a vapor-phase GAC system compared with uncontrolled values. This increase was due to the presence of several compounds that are difficult to adsorb. These compounds increase the carbon requirement and hence the emission rate. Table 28 compares the results.

TABLE 27. EMISSIONS COMPARISON FOR THE HICKSVILLE MEK SITE

Pollutant	No controls, kg/h	Vapor-phase GAC, kg/h	Catalytic oxidation, kg/h
Uncontrolled VOC emissions	0.318		
HX			0.00
SO_2		2.438	0.014
NO_x		0.343	0.050
CO		0.086	0.010
VOC (nonmethane)		0.0048	0.0026
CO_2		390.3	58.52
Emissions from control option (excluding CO_2)		2.872	0.074
Net emissions decrease[a] (excluding CO_2)		-2.553	0.244

[a]Negative values indicate an overall emissions increase over the uncontrolled option. Positive values indicate a net decrease.

TABLE 28. EMISSIONS COMPARISON FOR THE SYLVESTER'S GILSON ROAD SITE

Pollutant	No controls, kg/h	Vapor-phase GAC, kg/h	Catalytic oxidation, kg/h
Uncontrolled VOC emissions	1.278		
HX			0.176
SO_2		3905	0.025
NO_x		550.1	0.114
CO		137.5	0.023
VOC (nonmethane)		7.64	0.006
CO_2		6.252×10^5	136.4
Emissions from control option (excluding CO_2)		4600	0.344
Net emissions decrease[a] (excluding CO_2)		-4599	0.934

[a]Negative values indicate an overall emissions increase over the uncontrolled option. Positive values indicate a net decrease.

Under this scenario, the boiler would have to be very large and would be subject to PSD review. Under normal circumstances, little or no consideration would be given to attempting to capture isopropyl alcohol. Acetone can also present special problems in terms of the use of a vapor-phase GAC system. Because this site uses its boiler as an incinerator, the net emission reduction predicted to result from the use of catalytic oxidation may be similar to actual operation at this site. Using the boiler to heat the water would tend to increase the net emissions resulting from the vapor-phase GAC system option.

5.3 SUMMARY

In each case the selection of vapor-phase GAC adsorption as a control option results in a net increase in the overall emissions. In cases where large quantities of carbon would be required, the net emission increases could be substantial and may necessitate a rethinking of the need or desire to control such compounds. Such results would also indicate another alternative would be more appropriate.

A smaller net emissions increase was generally predicted for the catalytic oxidation option than for the GAC option because the heat input and emissions are controlled more by gas volume than by the chemical composition of the gas stream. The Tacoma Well 12A Site was the only one where the emissions from the operation of catalytic oxidation were much larger than those from carbon adsorption. These larger emissions were due to the high gas volumes that would have to be handled by the oxidizer. A net emissions decrease was predicted for both HTAS because of the reasonable gas volumes and the high operating temperatures. Actual net emission reductions would probably be less because of the boiler operation for heating the water going to the stripper.

With the focus on air-stripper performance, these net emissions increases or decreases tend to be overshadowed or not even considered. The ASPEN model provides a method for at least comparing net emissions increases

or decreases for evaluation of existing designs or potential control alternatives. This could also be used to indicate the need for other reviews such as a PSD review for new major sources, as was shown for four sites with the vapor-phase carbon adsorption option.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The first major objective of the project was to provide a straightforward method of inputing data for the ASPEN air stripper and control option modules while keeping the programming requirement transparent to the user. The user-interface software provides this by allowing the user to input data through a series of menus with default values available to evaluate existing designs and new design options for sizing and cost purposes. A user's guide and documentation have been developed and are supplied as a separate document.

The second major goal of this project was to develop an output report format that provided the most information in a usable format. The default printing characteristics are inherently cryptic and are displayed in less familiar units than most people are used to reading. The report format developed under the project converts these ASPEN software outputs to more conventional and familiar units (e.g., percentage removal, kg/h, etc).

The third major goal of this project was to compare the predicted performance with actual performance for a sampling of air strippers operating under a variety of conditions and treating several different chemicals. Seven strippers were selected for comparison. Twenty-five different compounds were evaluated for strippers with air/water ratios ranging from 20:1 to 300:1. In general, performance predicted by the ASPEN model matched the actual performance within 1 percent relative accuracy. In some isolated instances the predicted performance did not match the observed performance, generally for compounds such as methyl ethyl ketone and dichloromethane. In some cases, the cause of the discrepancy could not be determined.

A small number of compounds were not included in the ASPEN library of chemicals. For these compounds (e.g., 1,1-dichloroethylene, 1,2-dichloroethylene, and 1,1,1-trichloroethane), the selection of a surrogate compound

that was chemically similar (i.e., similar in structure and molecular weight) was required. A greater relative error was noted for most simulations when surrogate chemicals were used. Again, the error was generally within 4 percent of the actual value.

One tentative conclusion derived from these simulations is that the ASPEN model tends to overpredict performance slightly at lower air/water ratios (less than 50:1) and to underpredict slightly at higher air/water ratios. More study of this situation would require many more stripper designs to be evaluated. This seems plausible, however, because nonideal effects (channeling) would tend to occur more often at lower air/water ratios than at higher ones.

One area in which data were lacking concerned cost comparisons. Costs were often quoted with only limited or no supporting data or assumptions available from the site. Therefore, only limited cost comparisons were possible, and it was sometimes difficult to tell which items were included in site costs estimates so that a meaningful comparison could be made.

Limited control option comparisons could be made for sites where controls were used. Both sites using vapor-phase GAC control did not match the ASPEN model design exactly because the ASPEN model assumes steam regeneration. The ASPEN model could be used, however, for evaluation of the carbon requirements and a comparison of existing designs. The output suggested that the two designs evaluated were inadequate to provide a high degree of VOC removal. Limited site data confirmed this, as VOC removal efficiency was very low at these two sites and substantially below design values. Results in these two cases suggest that some other control option would be appropriate and/or that better monitoring of performance was needed.

The fourth major goal of this project was to evaluate the emissions tradeoffs that occur when controls are applied to air strippers. Each of the seven selected sites was run on the ASPEN simulation to develop control equipment designs for the air stripper off-gas. In general, the application of emission controls resulted in a net increase in total emissions although VOCs were controlled. These conclusions were based on energy-usage calculations and emission factors. It was also predicted that, except for very large air flows, the use of vapor-phase GAC adsorption with steam regeneration results in a larger net emissions increase than does catalytic

oxidation. In addition, for some systems, adequate control of certain compounds (such as vinyl chloride and dichloromethane) may be impractical. The ASPEN software does not attempt to weigh the toxics effects of the uncontrolled VOC emissions against other emissions. It simply indicates how much of particular pollutants will be generated.

6.2 RECOMMENDATIONS

The modules assembled for this version of the ASPEN software represent the most common stripper design and most probable emissions control options. An additional option of nonregenerable vapor-phase GAC would probably be useful in the future. The program has shown itself to be versatile enough to simulate HTAS. To date, however, only limited application of this technique has been seen at actual Superfund sites.

An alternative that may see more use in the future is cross-flow stripping. This technique can be used in situations where relatively high concentrations of easily stripped compounds (Henry's Law constants = 10^{-2} to 10^{-3} atm.m^3/mol) can be stripped with low air/water ratios, which results in low air volumes requiring control. More-difficult-to-strip compounds (Henry's Law constants = low 10^{-3} to high 10^{-5} atm.m^3/mol) can then be stripped in a second column operating at much higher air/water ratios. An example of such a system is shown in Figure 10. This may become a viable system in the future to reduce control costs and may compete with traditional systems. If this system appears to be a viable approach, an additional module for ASPEN should be considered, as such a simulation now could only be achieved by running the ASPEN simulation at least twice and using the results of one run as the input for the second.

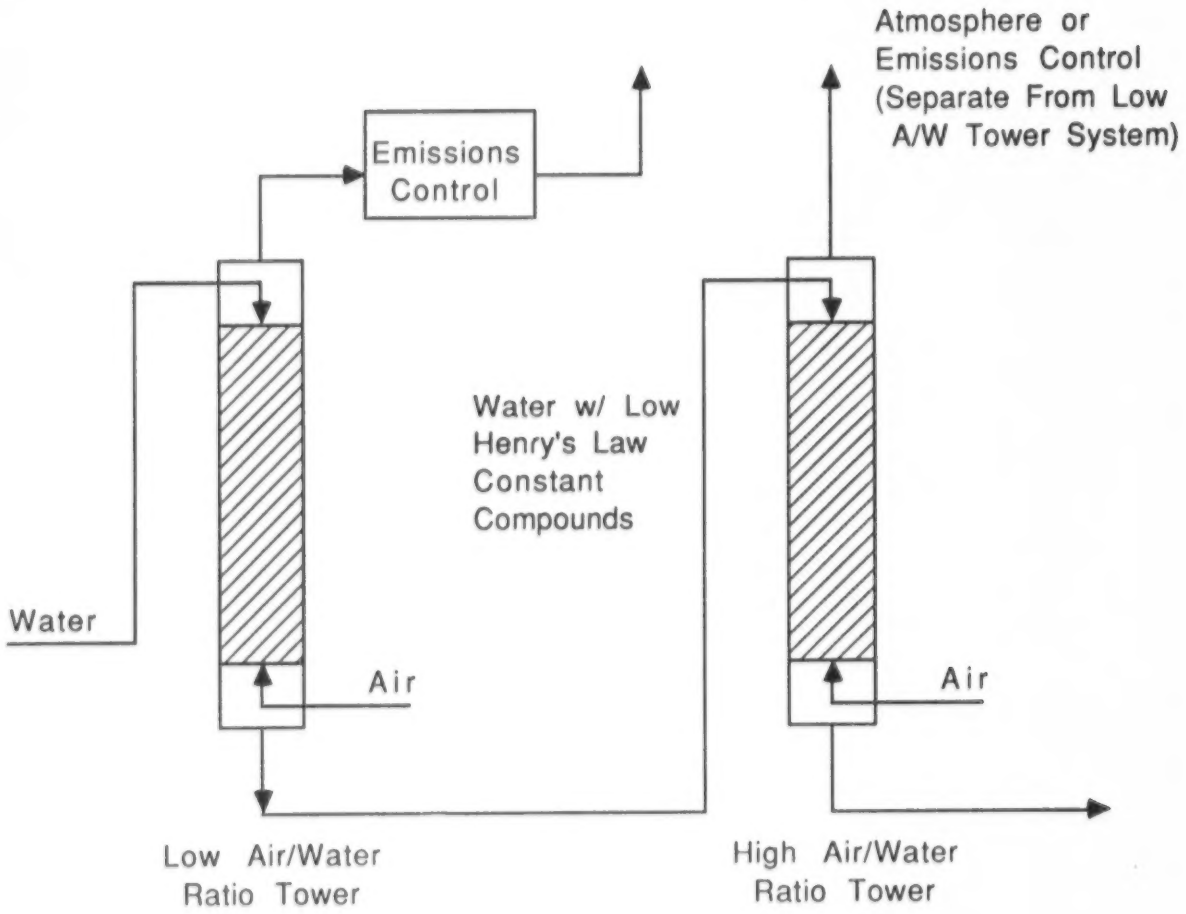

Figure 10. Process flow diagram for "cross-flow" air stripper for handling reduced gas volumes.

REFERENCES

1. Radian Corporation. Air Stripping of Contaminated Water Sources Air Emissions and Controls. Prepared for the U.S. Environmental Protection Agency. July 1987.

2. U.S. Environmental Protection Agency. Compilation of Air Pollutant Emission Sources. AP-42, Fourth Edition. September 1985.

APPENDIX A

SUMMARY OF SITE PARAMETERS

TABLE A-1. AIR STRIPPER LOCATIONS AND CONTRACTS

Site number	Site name and location	State/local contact and phone	EPA/Superfund contact and phone	Startup date	Operating hours per year	Type of emissions control
1	Tacoma Well 12A Tacoma, WA Pierce County	Ken Merry Tacoma Public Utilities (206) 593-8210	Kevin Rochlon Region X (206) 442-2106	July 1983	2500	None
2	Rockaway Township Rockaway Township, NJ Morris County	Steve Levinson Rockaway Dept. of Health (201) 627-7200 Mary Lou Parm NJ DEP (609) 292-5383		February 1982	8760	None
3	Brewster Well Field Village of Brewster, NY Putnum County		Robert Wing Region II (212) 264-8670	October 1984	8760	None
4	Verona Well Field Battle Creek, MI Calhoun County	Pat McKay Michigan Dept. of Natural Resources (517) 373-8448		September 1984	8760 GAC (nonregenerable)	Vapor-phase
5	Western Processing Kent, WA King County		Loren McPhillips Region X (206) 442-4903	September 1988	Not established with fume incinerator	Vapor-phase GAC (CADRE)
6	Hicksvillle MEK Spill Site Hicksville, NY Nassau County		Robert Cobiella Region II (201) 321-6646	June 1984	3 months under removal action	None

(continued)

TABLE A-1 (Continued)

Site number	Site name and location	State/local contact and phone	EPA/Superfund contact and phone	Startup date	Operating hours per year	Type of emissions control
7	Gilson Road Site (Sylvester's) Nashua, NH Hillsborough County	Robert Ostrofsky NH Dept. of Environmental Services (603) 882-3631	Chet Janowski Region I (617) 573-9623	June 1986	8760	Boiler/Incinerator

TABLE A-2. AIR STRIPPER AIR AND WATER FLOWS

Site number	Water flow				Dry air flow				Water vapor			Air and water vapor		
	°C	kg/h	kmol/h	m^3/h	°C	kg/h	kmol/h	m^3/h	kg/h	kmol/h	m^3/h	kg/h	kmol/h	m^3/h
1	10.0	788,720	43,818	794.9	10.0	295,974	10,241	246,357	3,848.7	213.8	2,332.7	299,823	10,455	248,691
2	11.8	315,488	17,527	318.0	20.0	76,545	2,649	63,713	491.9	27.3	645.5	77,037	2,676	64,359
3	12.8	67,605	3,756	68.1	15.6	4,093	141.6	3,407	10.6	0.6	13.9	4,104	142.2	3,421
4	12.8	439,430	24,413	442.9	20.0	10,206	353.1	8,495	66.3	3.7	87.0	10,272	356.8	8,582
5	7.2	22,535	1,252	22.7	11.4	4,389	151.8	3,653	28.5	1.6	37.4	4,417	153.4	3,690
6	88.0	21,938	1,218	22.7	29.0	3,266	113.0	2,718	21.2	1.2	27.7	3,287	114.2	2,746
7	79.4	68,101	3,780	68.1	43.3	4,205	145.5	3,500	27.5	1.5	35.9	4,232	146.9	3,536

TABLE A-3. ORGANIC CONTENT OF WATER STREAMS

Site number	Chemical contaminant	Design, ppb	Water entering stripper			Water leaving stripper			Weight removal efficiency, %
			ppb	kg/h	kmol/h	ppb	kg/h	kmol/h	
1	1,1,2,2-Tetrachloroethane	300	40.9	0.033	1.935×10^{-4}	2.05	0.002	9.70×10^{-6}	95.0
	trans-1,2-Dichloroethylene	100	14.3	0.011	1.172×10^{-4}	ND		99.9	
	Trichloroethylene	130	44.6	0.035	2.706×10^{-4}	ND		99.9	
	Tetrachloroethylene	5	0.9	0.001	4.31×10^{-6}	ND		99.9	
	Total VOC	535	100.7	0.080	5.86×10^{-4}	2.05	0.002	9.70×10^{-6}	97.5
2	Trichloroethylene		28.3	0.0090	0.0001	ND		99.99	
	Diisopropyl ether	4,000	ND			ND			
	Methyl-tert-butyl ether		3.2	0.0010	1.15×10^{-5}	ND		99.99	
	1,1-Dichloroethylene		4.0	0.0013	1.31×10^{-5}	ND		99.99	
	cis-1,2-Dichloroethylene		6.4	0.0020	2.10×10^{-5}	ND		99.99	
	Chloroform		1.3	0.0004	3.47×10^{-6}	ND		99.99	

(continued)

TABLE A-3 (Continued)

Site number	Chemical contaminant	Design, ppb	Water entering stripper			Water leaving stripper			Weight removal efficiency, %
			ppb	kg/h	kmol/h	ppb	kg/h	kmol/h	
	1,1,1-Trichloroethane		20.0	0.0064	4.78×10^{-5}	ND		99.99	
	Dichloromethane		ND			ND			
	1,1,-Dichloroethane		2.0	0.0006	6.42×10^{-6}	ND		99.99	
	Total VOC		65.2	0.0207	0.0002			99.99	
3	Tetrachloroethylene	215	200	0.0136	0.0821	3	0.0002	1.23×10^{-6}	98.50
	Trichloroethylene	77	30	0.0020	0.0152	2	0.0001	1.04×10^{-6}	93.33
	1,2-Dichloroethylene	68	38	0.0026	0.0268	3	0.0002	1.40×10^{-6}	95.59
	Vinyl chloride	2	ND						
	Total VOC	362	268	0.0182	0.1241	8	0.0005	3.67×10^{-6}	97.01
4	1,1-Dichloroethane	34	6.6	0.0029	2.93×10^{-5}	0.5	0.0002	2.02×10^{-6}	98.53
	1,2-Dichloroethane	8	4.1	0.0018	1.82×10^{-5}	2.9	0.0013	1.31×10^{-5}	29.27

(continued)

TABLE A-3 (Continued)

Site number	Chemical contaminant	Design, ppb	Water entering stripper			Water leaving stripper			Weight removal efficiency, %
			ppb	kg/h	kmol/h	ppb	kg/h	kmol/h	
	1,1,1-Trichloroethane	150	10.3	0.0046	3.46×10^{-5}	2.4	0.0011	8.27×10^{-6}	76.70
	cis-1,2-Dichloroethylene	229	15.3	0.0068	0.0001	2.6	0.0012	1.24×10^{-5}	83.01
	1,1,-Dichloroethylene	11	1.0	0.0004	4.12×10^{-6}	ND		99.99	
	Trichloroethylene	62	2.1	0.0009	6.87×10^{-6}	ND		99.99	
	Tetrachloroethylene	94	16.4	0.0073	4.40×10^{-5}	ND		99.99	
	Dichloromethane		41.2	0.0182	0.0002	13.9	0.0062	0.0001	66.26
	Vinyl chloride		34.0	0.0151	0.0002	ND		99.99	
	Total VOC		131.0	0.0580	0.0007	22.4	0.0099	0.0001	82.90
5	Benzene	2,000	73	0.0017	2.18×10^{-5}	5	0.0001	1.28×10^{-6}	93.15
	Carbon tetrachloride	700	5	0.0001	6.49×10^{-7}	5	0.0001	6.49×10^{-7}	0
	Chloroform	20,000	781	0.0177	0.0001	5	0.0001	8.40×10^{-7}	99.36

(continued)

TABLE A-3 (Continued)

Site number	Chemical contaminant	Design, ppb	Water entering stripper			Water leaving stripper			Weight removal efficiency, %
			ppb	kg/h	kmol/h	ppb	kg/h	kmol/h	
	1,1-Dichloroethane	17,000	ND						
	1,2-Dichloroethane	8,000	22	0.0005	5.05×10^{-5}	5	0.0001	1.01×10^{-6}	77.27
	1,1-Dichloroethylene	500	89	0.0020	2.06×10^{-5}	5	0.0001	1.03×10^{-6}	94.38
	Fluorotrichloromethane	500	ND						
	1,1,1-Trichloroethane	300,000	1,440	0.0327	0.0002	5	0.0001	7.52×10^{-7}	99.65
	Trichloroethylene	200,000	8,220	0.1867	0.0014	5	0.0001	7.63×10^{-7}	99.94
	Vinyl chloride	300	159	0.0036	0.0001	1	2.27×10^{-5}	3.60×10^{-7}	99.37
	Dichloromethane	700,000	8,170	0.1856	0.0022	30	0.0007	8.24×10^{-6}	99.63
	trans-1,2-Dichloroethylene	200,000	ND						
	Chloromethane	100	ND						

(continued)

TABLE A-3 (Continued)

Site number	Chemical contaminant	Design, ppb	Water entering stripper			Water leaving stripper			Weight removal efficiency, %
			ppb	kg/h	kmol/h	ppb	kg/h	kmol/h	
	Tetrachloroethylene	1,800	378	0.0086	0.0001	5	0.0001	6.02×10^{-7}	98.68
	Toluene	14,000	551	0.0125	0.0001	5	0.0001	1.09×10^{-6}	99.09
	1,2-Dichlorobenzene		11	0.0002	1.36×10^{-6}	5	0.0001	6.80×10^{-7}	54.55
	Hexachlorobutadiene		250	0.0057	2.18×10^{-5}	10	0.0002	7.66×10^{-7}	96.00
	Hexachloroethane		250	0.0057	2.41×10^{-5}	10	0.0002	3.35×10^{-6}	96.00
	Isobutanol		10	0.0002	2.70×10^{-6}	10	0.0002	2.70×10^{-6}	0
	Methyl ethyl ketone		1,480	0.0336	0.0005	440	0.0100	0.0100	70.27
	Nitrobenzene		250	0.0057	4.63×10^{-5}	10	0.0002	1.63×10^{-6}	96.00
	1,1,2-Trichloroethane		15	0.0003	2.26×10^{-6}	5	0.0001	7.32×10^{-7}	66.67
	Total VOC		22,154	0.5032	0.0049	566	0.0126	1.43×10^{-3}	97.45
6	Methyl ethyl ketone	15,000	15,000	0.3407	0.0047	239	0.0049	0.0001	98.41

(continued)

TABLE A-3 (Continued)

Site number	Chemical contaminant	Design, ppb	Water entering stripper			Water leaving stripper			Weight removal efficiency, %
			ppb	kg/h	kmol/h	ppb	kg/h	kmol/h	
7	Isopropyl alcohol	36,000	532	0.0362	0.0006	26.8	0.0017	2.83×10^{-5}	95.30
	Acetone	36,000	472.7	0.0322	0.0006	42.7	0.0026	4.48×10^{-5}	91.93
	Toluene	22,000	14,884	1.0140	0.0110	20.7	0.0013	1.41×10^{-5}	99.87
	Dichloromethane	8,300	236.5	0.0161	0.0002	16.0	0.0010	1.18×10^{-5}	93.79
	1,1,1-Trichloroethane	430	1,340	0.0913	0.0007	7.8	0.0005	0.37×10^{-5}	99.45
	Trichloroethylene	740	1,017	0.0693	0.0006	3.5	0.0002	0.15×10^{-5}	99.71
	Chloroform	1,200	469	0.0320	0.0003	4.9	0.0003	0.25×10^{-5}	99.06
	Total VOC		18,951.2	1.2911	0.0138	122.4	0.0076	1.07×10^{-4}	99.41

TABLE A-4. COMPOSITION OF AIR LEAVING STRIPPER

Site number	Chemical compound	ppmv	kg/h	kmol/h	µg/m³
1	1,1,2,2-Tetrachloroethane	0.018	0.031	1.84×10^{-4}	125.8
	trans-1,2-Dichloroethylene	0.011	0.011	1.17×10^{-4}	44.6
	Trichloroethylene	0.026	0.035	2.71×10^{-4}	142.1
	Tetrachloroethylene	0.001	0.001	4.31×10^{-6}	4.1
	Total VOC	0.056	0.078	5.77×10^{-4}	316.6
2	Trichloroethylene	0.026	0.0090	0.0001	141.3
	Diisopropyl ether	ND			
	Methyl-tert-butyl ether	0.004	0.0010	1.15×10^{-5}	15.7
	1,1-Dichloroethylene	0.005	0.0013	1.31×10^{-5}	20.4
	cis-1,2-Dichloroethylene	0.008	0.0020	2.10×10^{-5}	31.4
	Chloroform	0.001	0.0004	3.47×10^{-6}	6.3
	1,1,1-Trichloroethane	0.018	0.0064	4.78×10^{-5}	100.4
	Dichloromethane	ND			
	1,1-Dichloroethane	0.002	0.0006	6.42×10^{-6}	9.4
	Total VOC	0.039	0.0207	0.0002	324.9
3	Tetrachloroethylene	0.58	0.0134	0.0821	3,999.8
	Trichloroethylene	0.10	0.0019	0.0152	557.7
	1,2-Dichloroethylene	0.18	0.0024	0.0268	704.4
	Vinyl chloride	ND			
	Total VOC	0.86	0.0177	0.1241	5,261.9
4	1,1-Dichloroethane	0.08	0.0027	2.73×10^{-5}	317.8
	1,2-Dichloroethane	0.01	0.0005	5.10×10^{-6}	58.9
	1,1,1-Trichloroethane	0.07	0.0035	2.63×10^{-5}	412.0
	cis-1,2-Dichloroethylene	0.16	0.0056	0.0001	659.2
	1,1-Dichloroethylene	0.01	0.0004	4.12×10^{-6}	47.1
	Trichloroethylene	0.02	0.0009	6.87×10^{-6}	105.9
	Tetrachloroethylene	0.12	0.0073	4.40×10^{-5}	859.3

(continued)

TABLE A-4 (Continued)

Site number	Chemical compound	ppmv	kg/h	kmol/h	μg/m³
	Methylene chloride	0.40	0.0120	0.0001	1,412.6
	Vinyl chloride	0.68	0.0151	0.0002	1,777.5
	Total VOC	1.56	0.0480	0.0005	5,650.3
5	Benzene	0.14	0.0016	2.05×10^{-5}	438.0
	Carbon tetrachloride	0	0	0	0
	Chloroform	0.97	0.0176	1.48×10^{-4}	4,818.0
	1,1-Dichloroethane				
	1,2-Dichloroethane	0.03	0.0004	4.04×10^{-6}	109.5
	1,1-Dichloroethylene	0.13	0.0019	1.96×10^{-5}	520.1
	Fluorotrichloromethane				
	1,1,1-Trichloroethane	1.61	0.0326	2.45×10^{-4}	8,924.2
	Trichloroethylene	9.37	0.1866	1.42×10^{-3}	51,081.3
	Vinyl chloride	0.38	0.0036	5.71×10^{-5}	985.5
	Dichloromethane	14.32	0.1849	2.18×10^{-3}	50,615.9
	trans-1,2-Dichloroethylene				
	Chloromethane				
	Tetrachloroethylene	0.34	0.0085	5.12×10^{-5}	2,326.8
	Toluene	0.89	0.0124	1.35×10^{-4}	3,394.4
	1,2-Dichlorobenzene	4.48×10^{-3}	0.0001	6.80×10^{-7}	27.4
	Hexachlorobutadiene	0.14	0.0055	2.11×10^{-5}	1,505.6
	Hexachloroethane	0.15	0.0055	2.32×10^{-5}	1,505.6
	Isobutanol	0	0	0	0
	Methyl ethyl ketone	2.16	0.0236	3.28×10^{-4}	6,460.4
	Nitrobenzene	0.29	0.0055	4.47×10^{-5}	1,505.6
	1,1,2-Trichloroethane	0.01	0.0002	1.50×10^{-6}	54.7
	Total VOC	30.92	0.4841	4.70×10^{-3}	134,273.0
6	Methyl ethyl ketone	41.25	0.3358	0.0047	123,546.7

(continued)

TABLE A-4 (Continued)

Site number	Chemical compound	ppmv	kg/h	kmol/h	μg/m³
7	Isopropyl alcohol	3.95	0.0345	0.0006	9,857.1
	Acetone	3.51	0.0296	0.0005	8,457.1
	Toluene	75.61	1.0127	0.0110	289,342.9
	Methylene chloride	1.22	0.0151	0.0002	4,314.3
	1,1,1-Trichloroethane	4.69	0.0908	0.0007	25,942.9
	Trichloroethylene	3.62	0.0691	0.0005	19,742.9
	Chloroform	1.83	0.0317	0.0003	9,057.1
	Total VOC	94.43	1.2835	0.0138	366,714.3

TABLE A-5. AIR STRIPPER PARAMETERS

Site number	Air/water ratio			Stripping tower design specifications					
	kg/kg	m^3/m^3	kmol/kmol	Packing height, m	Number of trays	Tower diameter, m	Description of packing or trays	Water mass velocity, kg/m^2-s	Air mass velocity, kg/m^2-s
1	0.375	309.9	0.234	7.01	NA	3.66	1 inch Saddles	4.165	1.563
2	0.243	200.4	0.151	7.60	NA	2.70	3 inch Tellerettes	15.306	3.714
3	0.061	50.0	0.038	5.41	NA	1.45	1 inch Saddles	11.404	0.690
4	0.023	19.2	0.014	12.19	NA	3.05	3.5 inch Pall Rings	16.729	0.389
5	0.195	160.9	0.121	6.25	NA	1.22	2.0 inch Jaeger Tri-Pack	5.362	1.044
6	0.149	119.7	0.093	4.57	NA	1.09	2.0 inch Jaeger Tri-Pack	6.531	0.972
7	0.062	51.4	0.038	4.87	16	1.22	Koch Type 3	16.182	0.999

TABLE A-6. SUMMARY OF ASPEN COMPARISON

Site number	Actual site data and performance					ASPEN predictions	ASPEN comparison ratio
	Chemical contaminant	ppb	kg/h	kmol/h	Removal, %	Removal, %	Actual/ASPEN removal
1	1,1,2,2-Tetrachloroethane	40.9	0.033	1.94×10^{-4}	95.0	89.17	1.07
	trans-1,2-Dichloroethylene	14.3	0.011	1.17×10^{-4}	99.99	99.98	1.00
	Trichloroethylene	44.6	0.035	2.71×10^{-4}	99.99	99.98	1.00
	Tetrachloroethylene	0.9	0.001	4.31×10^{-6}	99.99	99.98	1.00
	Total VOC	100.7	0.080	5.86×10^{-4}	97.50	95.59	1.02
2	Trichloroethylene	28.3	0.0090	0.0001	99.99	99.96	1.00
	Diisopropyl ether	ND					
	Methyl-tert-butyl ether	3.2	0.0010	1.15×10^{-5}	99.99	91.56	1.09
	1,1-Dichloroethylene	4.0	0.0013	1.31×10^{-5}	99.99		
	cis-1,2-Dichloroethylene	6.4	0.0020	2.10×10^{-5}	99.99	99.98	1.00
	Chloroform	1.3	0.0004	3.47×10^{-6}	99.99	99.96	1.00
	1,1,1-Trichloroethane	20.0	0.0064	4.78×10^{-5}	99.99	99.25	1.01
	Dichloromethane	ND					
	1,1-Dichloroethane	2.0	0.0006	6.42×10^{-6}	99.99	99.98	1.00
	Total VOC	65.2	0.0207	0.0002	99.99	99.29	1.01
3	Tetrachloroethylene	200	0.0136	0.0821	98.50	99.42	0.99
	Trichloroethylene	30	0.0020	0.0152	93.33	98.67	0.95
	1,2-Dichloroethylene	38	0.0026	0.268	95.59	99.67	0.96
	Vinyl chloride	ND				99.88	
	Total VOC	268	0.0182	0.1241	96.01	99.37	0.98
4	1,1-Dichloroethane	6.6	0.0029	2.93×10^{-5}	98.53	100.00	0.99
	1,2-Dichloroethane	4.1	0.0018	1.82×10^{-5}	29.27	88.85	0.33
	1,1,1-Trichloroethane	10.3	0.0046	3.46×10^{-5}	76.70	83.06	0.92

(continued)

TABLE A-6 (Continued)

Site number	Chemical contaminant	Actual site data and performance ppb	kg/h	kmol/h	Removal, %	ASPEN predictions Removal, %	ASPEN comparison ratio Actual/ASPEN removal
	cis-1,2-Dichloroethane	15.3	0.0068	0.0001	83.01		
	1,1-Dichloroethylene	1.0	0.0004	4.12×10^{-6}	99.99		
	Trichloroethylene	2.1	0.0009	6.87×10^{-6}	99.99	99.98	1.00
	Tetrachloroethylene	16.4	0.0073	4.40×10^{-5}	99.99	100.00	1.00
	Dichloromethane	41.2	0.0182	0.0002	66.26	99.14	0.67
	Vinyl chloride	34.0	0.0151	0.0002	99.99	100.00	1.00
	Total VOC	131.0	0.0580	0.0007	82.90	97.79	0.85
5	Benzene	73	0.0017	2.18×10^{-5}	93.15	99.95	0.93
	Carbon tetrachloride	5	0.0001	6.49×10^{-7}	0	99.97	0.00
	Chloroform	781	0.0177	0.0001	99.36	99.95	0.99
	1,1-Dichloroethane	ND					
	1,2-Dichloroethane	22	0.0005	5.05×10^{-6}	77.27	99.63	0.78
	1,1-Dichloroethylene	89	0.0020	2.06×10^{-5}	94.38	99.98	0.99
	Fluorotrichloromethane	ND					
	1,1,1-Trichloroethane	1,440	0.0327	0.0002	99.65	98.12	1.02
	Trichloroethylene	8,220	0.1867	0.0014	99.94	99.96	1.00
	Vinyl chloride	159	0.0036	0.0001	99.37	99.99	0.99
	Dichloromethane	8,170	0.1856	0.0022	99.63	99.97	1.00
	trans-1,2-Dichloroethylene	ND					
	Chloromethane	ND					
	Tetrachloroethylene	378	0.0086	0.0001	98.68	99.96	0.99
	Toluene	551	0.0125	0.0001	99.09	99.93	0.99
	1,2-Dichlorobenzene	11	0.0002	1.36×10^{-6}	54.55	99.52	0.55
	Hexachlorobutadiene	250	0.0057	2.18×10^{-5}	96.00		
	Hexachloroethane	250	0.0057	2.41×10^{-5}	96.00		
	Isobutanol	10	0.0002	2.70×10^{-6}	0.00	3.25	0.00
	Methyl ethyl ketone	1,480	0.0336	0.0005	70.27	48.17	1.46

(continued)

TABLE A-6 (Continued)

Site number	Actual site data and performance					ASPEN predictions	ASPEN comparison ratio
	Chemical contaminant	ppb	kg/h	kmol/h	Removal, %	Removal, %	Actual/ASPEN removal
	Nitrobenzene	250	0.0057	4.63×10^{-5}	96.00		
	1,1,2-Trichloroethane	15	0.0003	2.26×10^{-6}	66.67		
	Total VOC	22,154	0.5032	0.0049	97.45	96.21	1.01
6	Methyl ethyl ketone	15,000	0.3407	0.0047	98.41	96.79	1.02
7	Isopropyl alcohol	532	0.0362	0.0006	95.30	99.08	0.96
	Acetone	473	0.0322	0.0006	91.93	59.99	1.53
	Toluene	14,884	1.0140	0.0110	99.87	100.00	1.00
	Dichloromethane	236	0.0161	0.0002	93.79	100.00	0.94
	1,1,1-Trichloroethane	1,340	0.0913	0.0007	99.45	100.00	0.94
	Trichloroethylene	1,017	0.0693	0.0006	99.71	100.00	1.00
	Chloroform	469	0.0320	0.0003	99.06	100.00	0.99
	Total VOC	18,951	1.2911	0.0138	99.41	99.00	1.00